

DEPARTMENT OF THE INTERIOR

JOHN BARTON PAYNE, SECRETARY

BUREAU OF MINES

H. FOSTER BAIN, ACTING DIRECTOR

UNDERGROUND CONDITIONS
IN OIL FIELDS

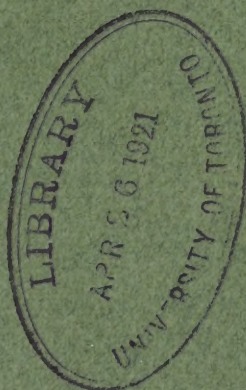
BY

A. W. AMBROSE

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A. W. AMBROSE



WASHINGTON
GOVERNMENT PRINTING OFFICE

1921

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First edition, December, 1920.

CONTENTS.

	Page.
Introduction.....	1
Acknowledgments.....	2
General statement.....	3
Purpose of report.....	3
Duties of the petroleum engineer.....	3
Problems of the study of underground conditions.....	5
General outline of major problems.....	5
Keeping of records.....	6
Importance and use of records.....	6
General outline of data to be prepared.....	7
Preparation of field maps.....	8
Location and elevation of wells.....	8
Field maps.....	9
Progress maps.....	11
Use of pins.....	11
Assembling of data and compilation of a well log.....	11
Review of histories of abandoned wells.....	15
Study on drilling and behavior of neighboring wells.....	16
Collection and compilation of individual well production records.....	17
Plotting of production records.....	17
Collection of samples of formations of water and of oil.....	19
Necessity for testing a drilling well.....	19
Productive horizons overlooked in hasty drilling.....	20
Collection of formation samples.....	20
Formation samples from a cable-tool well.....	21
Formation samples from a rotary well.....	22
Rotary core barrel.....	23
Testing samples of formation for oil.....	24
Examination of formation samples.....	25
Graphic presentation of underground conditions.....	26
Graphic well logs.....	26
Symbols.....	26
Abbreviations.....	29
Scale used.....	29
Speed in plotting.....	29
Plotting of graphic well logs.....	30
Historical graphic well log.....	32
Cross sections.....	34
Selection of the lines of cross sections.....	35
Projection of a well to a cross section.....	35
Plotting of a cross section.....	35
Cost of plotting.....	36
Selection of scale.....	36
Plotting.....	36

Problems of the study of underground conditions—Continued.

Graphic presentation of underground conditions—Continued.

Cross sections—Continued.

Page.

Correlation of cross sections.....	38
Aid of surface geology.....	38
Markers or key beds.....	38
Correlation and unconformities.....	40
Detection of faults in correlation.....	41
Apparent thickening of deeply tilted beds.....	41
Lenticularity and correlation.....	42

Graphic logs plotted to stratigraphic datum.....	44
--	----

Underground-structure contour map.....	46
--	----

Description of map.....	46
-------------------------	----

Preparation of map.....	46
-------------------------	----

Factors determining accuracy of map.....	47
--	----

Uses of map.....	48
------------------	----

Convergence map.....	49
----------------------	----

Data needed for a convergence map.....	50
--	----

Preparation of a convergence map.....	50
---------------------------------------	----

Use of convergence map to prepare a contour map of the oil sand.....	52
---	----

Peg models.....	52
-----------------	----

Use of peg models.....	52
------------------------	----

Preparation of peg models.....	52
--------------------------------	----

Stereograms.....	55
------------------	----

Drilling progress chart.....	55
------------------------------	----

Graphic charts applied to the oil industry.....	57
---	----

Daily well production of oil and water.....	57
---	----

Average daily well production of oil and water.....	58
---	----

Daily well production and trouble chart.....	58
--	----

Drilling well progress and casing depths.....	63
---	----

Time-depth reference chart for comparison of drilling wells.....	64
--	----

Daily receipts and deliveries of crude oil.....	64
---	----

Use of pins on maps.....	66
--------------------------	----

Need for a production engineer.....	66
-------------------------------------	----

Application of underground study to oil-field problems.....	67
---	----

General remarks.....	67
----------------------	----

Correlation of surface and underground geology.....	67
---	----

Water problems.....	68
---------------------	----

General remarks.....	68
----------------------	----

Trapping of oil underground.....	70
----------------------------------	----

Objections to water.....	72
--------------------------	----

Lifting water by compressed air.....	75
--------------------------------------	----

Selected bibliography on air lifts.....	78
---	----

Different waters in a well.....	78
---------------------------------	----

Contents of a sand.....	78
-------------------------	----

Different possible waters in a well.....	79
--	----

Top water.....	79
----------------	----

Bottom water.....	81
-------------------	----

Intermediate and middle water.....	82
------------------------------------	----

Edge water.....	84
-----------------	----

Water in the base of an oil sand.....	86
---------------------------------------	----

Lenticular water sand.....	86
----------------------------	----

Regional and local terminology of different waters.....	87
---	----

Application of underground study to oil-field problems—Continued.

Water problems—Continued.

	Page.
Chemical analyses of water.....	88
Investigation in Coalinga field, California.....	90
Interpretation of analyses.....	90
Properties of solutions.....	91
Radicles and their reacting values.....	92
Conversion of physical weights into reacting values.....	93
Derivation of special properties.....	94
Gradation of east side Coalinga waters.....	95
Top waters.....	95
Bottom waters.....	95
Intermediate waters.....	96
Persistence of properties of oil-field waters.....	96
Use of chemical properties of a well water in oil-field production problems.....	97
Application of water analyses in Coalinga field, California.....	97
Example 1.....	98
Example 2.....	99
Example 3.....	100
Application of water analyses in Gulf coast oil fields.....	103
General suggestions in use of water analyses.....	103
Collection of samples of water from wells for analysis.....	103
Application.....	104
Each field a separate problem.....	104
Form for computations.....	105
Selected bibliography.....	106
Use of detectors for tracing movement of underground waters.....	106
General remarks.....	106
Requirements of a detector.....	108
Organic dyes as detectors.....	108
Comparative value of various organic dyes for oil-field use.....	109
Fluorescein.....	110
Experiments with fluorescein in France.....	110
Use of fluorescein with the aid of the fluoroscope.....	111
Fluoroscope.....	111
Eosine.....	112
Methylene blue.....	112
Magenta.....	112
Congo red.....	112
Inorganic dyes as detectors.....	113
Potassium dichromate.....	113
Venetian red.....	113
Practical application of dyes in oil fields.....	113
When used.....	113
Placing of dye in well.....	114
Quantity used.....	114
Use of organic dyes in oil fields of California.....	115
Kern River field.....	115
Santa Maria field.....	115
Olinda and Salt Lake fields.....	116
Midway field.....	116
Coalinga field.....	117

Application of underground study to oil-field problems—Continued.

Water problems—Continued.

	Page.
The use of chlorides and other salts to determine underground flow.....	118
Chlorine method.....	118
Nitrates.....	119
Lithium salts as detectors.....	119
Slichter electrical method.....	119
Indications of a field going to water.....	121
Increase in water production.....	121
Increase in oil production.....	122
Increase in temperature of fluid.....	124
Use of pins and symbols.....	125
Field tests.....	125
Tests for top water.....	126
Tests for bottom water.....	127
Tests for intermediate water.....	127
Tests for edge water.....	127
Tests for water in the base of an oil sand.....	128
Tests on drilling well.....	128
Tests on water string of drilling well.....	129
Measurements.....	129
Bailing tests.....	131
Determination of the source of water in oil wells.....	134
Need of good records.....	134
Use of data.....	135
Mode of identifying sources of water in oil wells.....	135
Top water.....	136
Bottom water.....	137
Intermediate water.....	137
Edge water.....	138
Water in the base of an oil sand.....	138
Correction of wells making water.....	139
Top water.....	140
Use of packer to repair leak in water string.....	140
Screwing casing together to shut off top water.....	140
Driving water string to shut off top water.....	140
Forcing cement behind pipe to shut off top water.....	141
Use of liner to shut off top water.....	142
Redrilling or landing a new string of pipe to shut off upper water.....	143
Bottom water.....	143
Intermediate water.....	144
Edge water.....	145
Water in the base of an oil sand.....	146
Water in a lenticular sand.....	148
Protection of upper oil and gas sands.....	149
Encroachment of intermediate waters and methods of protecting upper oil sands by the use of mud-laden fluid.....	149
General statement.....	149
Early development.....	150
Original water line.....	151
Encroachment of water from 1908 to 1912.....	153

Application of underground study to oil-field problems—Continued.

Water problems—Continued.

Encroachment of intermediate waters and methods of protecting upper oil sands by the use of mud-laden fluid—Continued.	Page.
1918 water line.....	154
Rate of encroachment.....	154
Relation between structure and encroachment.....	155
Mud-laden fluid method of drilling developed to handle the conditions brought about by encroaching water.....	156
Necessity of properly protecting oil sands.....	156
Use of mud-laden fluid in rotary well to mud off upper oil sands.....	156
General suggestions in use of mud-laden fluid method.....	158
Savings of time and money by this method.....	158
Casing depths.....	159
Underground losses.....	160
General remarks.....	160
Losses due to improper or unsystematic casing.....	161
Losses in recovery methods.....	161
Losses due by a well out of control.....	162
Losses due to perforating all sands.....	163
Losses caused by not knowing producing zone.....	163
Losses caused by improper drilling methods.....	164
Losses in drilling through workable coal beds.....	165
Oil and gas sands—location of productive sands, their thickness and quality of oil.....	166
Location of producing and nonproducing sands.....	166
Thickness of sand and productivity.....	168
Discovery of new oil zone.....	169
Quality of oil.....	173
Discovery of deeper oil sand.....	174
Well depths.....	174
New well locations and extension of the field.....	175
Future well production.....	176
Gaging of oil wells.....	178
Importance of gaging.....	178
Barrels rather than per cent of water should be considered.....	179
Definition of terms.....	181
Methods of gaging.....	182
Actual measurement of oil and water.....	182
Periodical gages based upon production in a specified time.....	184
"Thieving" a sample of fluid from gage tank.....	186
Accuracy of lead line centrifuge tests.....	187
Preparation of gage table.....	189
Necessity for cheap method of gaging.....	190
Perforating and setting screen pipe.....	192
Fluid levels and tubing depths.....	193
General statement.....	193
Fluid levels may suggest source of water.....	194
Fluid levels may avoid skimming of oil.....	195
Fluid levels and future production.....	196
Study of fluid levels, tubing depths, and pumps to increase production.....	196

Application of underground study to oil-field problems—Continued.	Page.
Shooting of oil wells.....	197
Shooting of wells to overcome drilling and redrilling difficulties.....	198
Shooting of wells to increase production.....	199
Bibliography on oil-well shooting.....	200
Methods for recovering more oil from the oil-bearing formations.....	200
Forms for keeping records.....	201
General considerations.....	201
Driller's tour report.....	201
Instructions.....	206
Daily reports.....	206
Drilling reports.....	206
Casing records.....	206
Perforating records.....	207
Cleaning out.....	207
Reaming.....	207
Bailing records.....	207
Bridging and plugging records.....	207
Cementing records.....	207
Abandoning casing or tools.....	207
Daily drilling report.....	208
Weekly drilling and redrilling report.....	208
Well log.....	209
Daily gauge report of pumper.....	215
Daily individual well production.....	216
Plotting daily individual well production.....	217
Monthly individual well production.....	217
Yearly summary of monthly productions.....	219
Well cuts and gravities.....	222
Production of well while under observation.....	222
Daily gauges of field storage tanks or receiving tanks.....	223
Bailing and tubing record.....	223
Monthly tubing record.....	225
Report on work on wells.....	225
Cleaning well record.....	226
Daily report of idle hours for producing wells.....	227
Exchange of well data.....	227
Daily report showing irregular production features of wells.....	228
Computing water analyses.....	229
Publications on underground conditions in oil wells.....	230
Index.....	232

TABLES.

TABLE 1. Distribution of lost time on 25 wells.....	Page.
2. Results of use of organic dyes in Midway field, Calif.....	60
3. Collapsing pressures and capacities per linear foot of lapwelded casing of sizes commonly used in California.....	117
4. Daily production of well under observation.....	132
5. Sample gauge table used in converting height of fluid in gauge tanks to barrels.....	188
	189

FORMS.

	Page.
FORM 1. Specimen well-log record.....	13
2. Cards used at top of chart (Pl. XIII) for progress of wells and casing depths.....	65
3. Form for computing water analysis, as reported by the analyst, to Palmer's method of interpretation.....	105
4. Form for daily drilling report.....	202
5. Driller's tour report.....	205
6. Daily report of drillings.....	208
7. Weekly drilling report.....	209
8. Form for well log (front side).....	210
9. Form for well log (reverse side).....	211
10. Form for well log (reverse side).....	212
11. Form for well log (front side).....	213
12. Form of well record used in Oklahoma.....	214
13. Form for daily gauge report of pumper.....	215
14. Form for daily individual well production.....	215
15. Form for daily individual well report.....	217
16. Form for monthly individual well production.....	218
17. Form for monthly report of production.....	219
18. Form for yearly summary of monthly productions.....	220
19. Card for summary of monthly record of production.....	222
20. Form for well cuts and gravities.....	223
21. Form of daily gauges of field storage tanks.....	224
22. Form for bailing and tubing record.....	224
23. Form for monthly tubing record.....	225
24. Form for report of work on wells.....	226
25. Form for quarterly report on wells cleaned.....	226
26. Form for daily report of idle hours for producing wells.....	227
27. Form for exchange of well data.....	228
28. Form for daily report showing irregular production features of wells.....	229

ILLUSTRATIONS.

	Page.
PLATE I. Property map of a portion of the Midway oil field, Calif.....	10
II. A, Improvised rotary core barrel; B, Close-up view of improvised rotary core barrel.....	22
III. Cross section of wells of Sauer Dough Oil Co.....	40
IV. Section in Belridge field, Calif., illustrating the occurrence and correlation of lenticular sands, by T. E. Swigart.....	42
V. A, Peg model of Coyote Hills oil field, Calif.; B, Peg model of Union Oil Co., Santa Maria, Calif.....	48
VI. Stereogram of La Salle, Ill., and vicinity, showing the general geological structure and stratigraphy.....	50
VII. Stereogram showing characteristics of oil sand in Birds quadrangle.....	52
VIII. Progress chart of wells during drilling.....	54

	Page.
PLATE IX. Plot showing total daily production of oil and water, Western Oil Co., 1916.....	56
X. Average daily production of well No. 1, Western Oil Co., 1916.....	58
XI. Daily well production and trouble chart.....	60
XII. Chart for following progress of wells and casing depths.....	62
XIII. Time-depth reference chart for comparison of drilling wells.....	64
XIV. Chart to show daily receipts and deliveries of crude oil.....	66
XV. Container showing sand before it was saturated with oil.....	70
XVI. Container after sand was saturated with oil except lower part which was filled with water.....	71
XVII. Container after sand was flushed with water.....	76
XVIII. Two views of the air compressor equipment operated at one time by the Peerless Oil Co., now the Arizona Oil Co.....	77
XIX. Sketch showing encroachment of edge water, Coalinga anticline, Fresno County, Calif.....	150
XX. A, Crater of gas well taken after a loss of millions of cubic feet of natural gas; B, Crater formed by gas escaping to the surface 300 feet from the well.....	151
XXI. Diagram of well in Osage County, Okla.....	162
XXII. Sketch to show oil escaping up the side of casing and into formation, finally reaching the surface.....	164
XXIII. Tanks used for gaging oil and water by the Shell Co. of California, Oilfield, Calif.....	165
FIGURE 1. Model section, showing method of locating shallow and deep wells, also gas wells.....	10
2. Plot showing well production of oil and water.....	18
3. Plot showing how tools lost in hole decreased production.....	19
4. Suggested set of symbols plotted in two ways.....	27
5. Graduated scale used in plotting graphic well logs.....	30
6. Historical graphic well log showing history and graphic presentation of work on well.....	33
7. Sketch showing how horizontal scale smaller than vertical scale exaggerates the dip of a bed.....	36
8. Sketch showing advisability of selecting markers near oil horizon.....	40
9. Sketch showing how drill has to penetrate greater thickness of formation in steeply dipping beds.....	41
10. Well logs plotted to common stratigraphic datum to show the comparative well depths, water shut-offs, perforations, etc., of different wells.....	45
11. Convergence map showing by lines of equal distance (isochore lines) the vertical distance between the Ames limestone member and the hundred-foot sand in the Sewickley quadrangle.....	51
12. Sketch to show sand texture and original relation of oil and water.....	70
13. Sketch to show how fluid advances most rapidly through the coarse sands and the water thus traps the oil in the fine tight sand.....	71
14. Surface plat to show advance of oil-water contact lines through sands of different texture.....	72

	Page.
FIGURE 15. Plot showing increase of water in suspension and emulsion, in addition to an increase of free water, upon appearance of water in a well.....	75
16. Plot showing effect of water on oil production of a well.....	76
17. Hypothetical sketch to show different water sands.....	80
18. Sketch showing "cavings" keeping water out of oil sand.....	81
19. Sketch to illustrate additional cost of producing where there is a middle water.....	83
20. Map of area in vicinity of Dropped dome, Cushing oil field, Oklahoma, showing edge-water line cutting across structure contour of Layton sand.....	84
21. Sketch to show edge-water line cutting across structure contours, due to excessive development locally.....	85
22. Sketch showing lenticular sands.....	87
23. Sketch, showing production of oil well before and after plugging off bottom water.....	99
24. Graphic sketch showing reacting values in percentage of radicals in waters of different sands and condition of hole when samples were collected.....	101
25. Plot showing increase in oil production from well prior to encroachment of edge water.....	123
26. Sketch showing how water in base of oil sand may trap oil....	148
27. Cross section showing position of edge water, East Side Field, Coalinga, Calif.....	151
28. Sketch showing entrance of oil sand from imperfect seating of casing and lack of cement around bottom of outer casing....	162
29. Sketch showing entrance of water into oil sand and its migration to a properly drilled well, from the use of only one string of casing in first well.....	163
30. Sketch showing entrance of water into oil sand from withdrawal of casing from an abandoned well without placing a plug between oil and water sands.....	164
31. Sketch showing entrance of water from lack of uniformity of distance of shut-off below water sands when two wells penetrate the same strata.....	165
32. Sketch showing entrance of water because shut-off was made at the same depth in two wells without consideration of the fact that strata most frequently do not lie parallel to the ground surface.....	166
33. Sketch showing entrance of water into a properly drilled well because another well drilled into a water-bearing sand below the oil sand, but did not plug the lower part of the hole.....	167
34. Sketch showing entrance of water into a properly drilled well because a neighboring well entered a deeper oil sand without inserting an extra string of casing to protect the first sand.....	168
35. Sketch showing presence of edge water due to a natural condition.....	169
36. Generalized sketch showing unsystematic casing of wells....	170
37. Sketch showing how upper oil sands were passed by.....	171

FIGURE 38. Sketch showing the relation between total production per acre (in barrels) and geologic structure in the Boston pool, Okla.....	177
39. Plot of monthly production of well, showing effect of water upon oil production.....	180
40. Settling tank placed at oil well by American Petroleum Co., Coalinga, Calif., to separate oil and water, and for gaging gross oil.....	185
41. Homemade thief to obtain samples of fluid from a tank.....	186
42. Fluid level curves.....	195
43. Plot showing relative well locations, for insertion in book con- taining yearly summary of monthly publications.....	221

UNDERGROUND CONDITIONS IN OIL FIELDS.

By A. W. AMBROSE.

INTRODUCTION.

The output of oil and gas from the producing fields in the United States is rapidly declining. Coincident with this decline is a steadily increasing demand for petroleum and its products, but at present there are no commercial substitutes for gasoline and lubricating oil.

Undoubtedly, many new fields will be discovered in this country during the next few years. Indeed, there may be periods of temporary flush production that for a few months or a year or perhaps two years will afford a surplus. Such peaks are temporary and should not be given too much weight in considering the relation between petroleum supply and our national life. In considering this problem we must regard a long period of time, and, if we do that we shall see that domestic production will be unable to keep pace with consumption. Hence, the public good demands that the highest efficiency obtainable be practiced in the production of oil.

To accomplish this end, the operator of to-day should so organize his forces for development and production that he recovers every barrel of oil that can be recovered at a profit. This necessarily involves the use of economical and scientific methods of development and production and the elimination of waste.

The Bureau of Mines has for years urged the conservation of petroleum and its products, and has pointed out that such conservation should start before the oil is brought to the surface rather than after it is in storage tanks. Losses of petroleum underground have undoubtedly been far greater than losses in storage, in transportation, and in refining. The quantity lost usually is indeterminate, and hence difficult to express in terms of money, but by remembering that entire oil fields have been ruined by invading waters some idea may be gained of the importance of underground waste.

The petroleum engineer is coming to be recognized as an extremely important aid in the intelligent development of oil fields. In this paper an effort is made to outline for the engineer and producer a field of work whereby science and engineering not only can but have been applied practically. The mining engineer has been the direct-

ing hand in the development of mines, and it is being recognized more and more that the petroleum engineer has a similar function in developing oil properties.

This paper aims to show the general method of procedure in studying underground conditions in producing oil fields and how such study may not only correct but even prevent great unnecessary losses. Such work provides the company with maximum insurance for the field against loss and is accomplished at minimum cost and minimum risk.

Throughout the paper reference is made to oil wells and oil fields, but to a certain degree many of the suggestions relating to oil wells are applicable in the care and protection of gas wells and in solving gas problems.

ACKNOWLEDGMENTS.

The writing of this paper was first suggested by W. A. Williams, formerly chief petroleum technologist of the Bureau of Mines; his successor, Chester Naramore, offered many valuable suggestions, and the present chief petroleum technologist, J. O. Lewis, also R. E. Collom, and Carl H. Beal, formerly a member of the bureau, have given constructive criticisms of great aid in the preparation of this paper, E. D. Nolan prepared the chapter on "Encroachment of intermediate waters and methods of protecting upper oil sands by the use of mud-laden fluid." The chapter "Graphic charts applied to the oil industry" was furnished by C. E. Sampson. E. W. Waggy, petroleum engineer of the bureau, furnished information on the subject of lifting water by compressed air. "A concrete example of correlation of lenticular sands" was prepared by T. E. Swigart.

Mr. J. C. van Eck kindly permitted the use of data previously prepared, by the writer, for the Shell Co. of California, under the direction of Mr. B. H. van der Linden. W. E. Perdew and H. H. Hill constructively criticized the chapter on "Flow detectors," and Mr. Perdew's criticism, because of his previous experience with the Slichter electrical method, was particularly helpful. Valuable information on organic dyes was furnished by Dr. Eugene Merz and Mr. August Merz, of Heller & Merz Co., Newark, N. J. The manuscript was read and criticized by J. O. Lewis, Carl H. Beal, R. E. Collom, F. B. Tough, E. W. Waggy, Tom Cox, and B. H. Scott.

Especial thanks for miscellaneous information noted throughout the text and for criticisms are due to Messrs. K. C. Heald, E. D. Nolan, W. C. McDuffie, Logan Burrell, H. L. Hamilton, W. W. Scott, R. Van A. Mills, David Donoghue, E. DeGolyer, Alexander Deussen, John R. Suman, C. S. Thomas, B. E. Parsons, E. G. Woodruff, W. B. Blodget, A. R. Elliott, and Miss E. H. Burroughs.

The author wishes to express his appreciation for suggestions to Mr. M. L. Requa and Mr. J. C. McDowell. J. G. Shumate, of the Bureau of Mines, helped prepare the diagrams and other illustrations.

GENERAL STATEMENT.

PURPOSE OF REPORT.

As has been indicated, the purpose of this bulletin is to point out the general method of procedure in studying underground conditions in oil fields and to place before the petroleum industry the results of proper cooperation between the so-called technical men and the practical men who have applied engineering methods to the development of oil fields. The bulletin should serve as a guide to the petroleum engineer in solving oil-field problems and may point out to him studies that should be made in oil-field development.

Much of the paper is devoted to a solution of water problems, as these are among the most important confronting the petroleum engineer. However, the bulk of the data prepared for a solution of water problems can be used for many other things—for example, the cross sections prepared can be used in studying well depths, casing depths, location of sands, etc.

DUTIES OF THE PETROLEUM ENGINEER.

In the development of an oil property there is the need of a man who corresponds to the mining engineer of a large mining property. Some oil companies may style such an employee a resident geologist, a resident engineer, or a petroleum technologist. In this paper he is termed a petroleum engineer. His duties are to apply his scientific and geological training practically to oil-field development. He should be by education a mining, civil, or mechanical engineer, with a working knowledge of geology and chemistry.

Often the relation between the technical and nontechnical man is not cordial. Now, the fundamental purpose in the handling of a property is efficient operation and this can not be effected best until estrangements are ameliorated. There is no reason why most cordial relations can not be established between the driller and the engineer, providing each show a leniency. Each should realize that the other is a specialist in his own work. The engineer should appreciate that the record of conditions underground, as shown in well logs and histories, largely represents the results of the driller's observation. Hence the engineer should discuss with the driller the practical application of engineering methods so that the latter will take particular care to collect formation samples or other data needed in

solving the engineer's problems. The driller is most familiar with the formations, as he understands how they drill, so each day the engineer should discuss the daily well report with the driller.

The duty of an engineer experienced in oil-field development work is to direct the many problems outlined on pages 5 and 6. At first his responsibilities will be limited until he has been able to work out the underground conditions on the property and to have his records, data, and other information compiled in such a form that they are readily accessible. As he becomes more experienced and proficient he will be able to take over more and more of the operating side until he becomes a highly valuable adjunct to the management.

In the development of oil fields, it is of the utmost importance that the proper kind of data be collected, and for companies whose records are incomplete or have not been properly kept, forms should be prepared immediately for collecting the data desired.

Wells should be gaged daily, both for oil and for water. Exceedingly valuable information will thus be built up which will be worth many times its cost during the life of the property. A record of water content will be useful in locating the source of water troubles. The production records will give valuable data on the future worth of the property and on the effect of various methods of operation on the production of individual wells and of the property as a whole—for example, the application of vacuum pumping, or the effect of shooting or of cleaning out wells. In the later life of the property the production records will enable the producer to determine which wells are profitable and which are not.

From a study of production records the locations that are likely to prove most productive can be chosen. Such study will take into account the condition of the sands and their structure, in order to avoid "tight" parts of the sand or to avoid parts of the field that carry water or gas. Production records are also of value in estimating the future production of wells and of the property.

A highly important problem is the locating of all water sands and the determining of proper depths of casing. To solve this problem, complete production records and all additional information possible in relation to the wells and their production should be collected. After the various water sands have been determined, necessary recommendations should be made for the correction of wells making water. When the water sands have been definitely located, it is possible to choose the casing depths, well depths, and well locations, all being selected so as to avoid water troubles.

A knowledge of surface and subsurface geology permits the selection of well locations that are best situated structurally, or

under certain conditions the selection of sites that will give definite or desired information as to the future of the field.

Samples of the formations and samples of water should be collected; they may be labeled and stored for examination if needed. This sampling involves only a small expense and may later prove helpful in solving some problem. The engineer should interest the drillers in collecting these samples and make use of their reports.

All of the above data should be collected upon advice of the engineer; he should study them in conjunction with the foremen and then prepare recommendations to the management. These recommendations should be followed unless the superintendent or other person in authority can show to the management that they are at fault. Predictions should be made with discretion, however, and the engineer should be certain that the assembled information justifies the conclusions drawn.

The field of work of the petroleum engineer covers every phase of development and production to which chemistry, engineering, and geology can be applied. The tendency is more and more for the engineer to work into the operating side of the business, just as in the mining industry. After some years of actual contact with the problems of such work and a study of the practical aspects of oil-field problems, the engineer may render service of high value, for he will then have the advantages of education and the scientific study of the problems of development and production, and in addition will have a first-hand knowledge of details of operation.

PROBLEMS OF THE STUDY OF UNDERGROUND CONDITIONS.

GENERAL OUTLINE OF MAJOR PROBLEMS.

Many companies have found that a few technically trained engineers cooperating with the field men are able to offer suggestions and recommendations which save the company a great deal of money. In addition, the engineers have provided against many unnecessary losses. Such a procedure affords the company a form of insurance for its property at a small cost. In this bulletin are illustrations showing what was done on special problems. Some of the major problems to be solved and some of the work to be handled in properly protecting a field may be outlined as follows:

1. Keeping of records. See pages 6 and 7.
2. Preparation of data. See pages 7 to 67.
3. Correlation of surface and underground geology. See pages 67 and 68.
4. Water problems. See pages 68 to 158.

5. Casing depths. See page 160.
6. Underground losses. See pages 160 to 165.
7. Oil sands; location of productive sands, their thickness and quality of oil. See pages 166 to 174.
8. Well depths. See page 174.
9. New well locations and extension of the field. See page 175.
10. Future well production. See pages 176 and 177.
11. Gaging of oil wells. See pages 178 to 191.
12. Perforations and setting screen pipe. See page 192.
13. Fluid levels and tubing depths. See pages 193 to 196.
14. Shooting of oil wells. See pages 197 to 200.
15. Methods for extracting more oil from the oil-bearing formations. See page 200.

The above subjects are discussed in the succeeding pages.

KEEPING OF RECORDS.

IMPORTANCE AND USE OF RECORDS.

Records form the basis for the successful operation of any company. The expense of compiling records is negligible in comparison with the need of records and the results obtained by their use. A company that has no complete system of records should immediately prepare forms for recording data and give attention to the collection of data for these forms. The records needed vary with each district, and for each field a set should be adopted that will best meet the needs of each property.

Practically all operators, and particularly all successful operators, agree on the necessity of good records—records that tell what the wells have done, are doing, and may be expected to do. Every operator realizes the value of records of sales of oil and should place almost equal value on records of well logs and on histories of the past and present performances of wells.

At the start there should be little fear of an overabundance of material, for in endeavoring to cut down on detail the inexperienced engineer may omit important facts. Experience will soon teach a man to distinguish between important and unimportant features.

Records should be kept in systematic, coordinated form, so that all information is readily accessible. A uniform system is established as easily as any other and will greatly facilitate the keeping of future records.

Files should be so arranged that the engineer can readily find such data as the superintendent is likely to desire. If the superintendent must wait while a search is made through a mass of jumbled information, he naturally will not be inclined to call upon the engineer

often. To facilitate reference to the files the writer strongly indorses the use of letter-size sheets, $8\frac{1}{2}$ inches by 11 inches, for all office forms. For such notes as may be made in the field a pocket-size book is obviously handier.

Complete records of each well should be kept from the time the location and elevation are determined until the well is abandoned. The engineer should review old records often enough to be familiar with the past performance of the various wells and with the conditions that affect production.

The lack of good records of old natural-gas wells was a serious handicap in the recent search for helium-bearing gases, the helium being needed for war use in balloons and airships. In many fields the search for inert gases showed that the only information available on some wells was a report from a farmer that the gas would not burn. Often there were no records of the formations, the depth, the rock pressure, the open flow, or the casing. The work on taxation for the Internal Revenue Bureau, of the Treasury Department, showed an astonishing lack of much needed records.

Certainly it is not necessary to point out the many uses of records. The reader will see in the following pages that trustworthy records are absolutely essential for the proper operation of any oil or gas property. The forms to be used and their method of preparation in connection with records are discussed in the chapter on Forms.

GENERAL OUTLINE OF DATA TO BE PREPARED.

After the information needed for solving an oil-field problem has been compiled into compact records, it should be worked up in graphic form. Material collected or compiled for any one problem generally serves for several. For example, the cross sections and structure contour maps used in a water study are useful in the study of casing depths, well depths, location of oil and gas sands, and many of the other problems that have been outlined. Hence, in the discussion that follows the writer proceeds as though the operator desired the underground conditions worked up for a study of many problems rather than of one special problem.

An outline for the collection and preparation of data used in a general study of underground conditions is given below. The order of the preparation of information should not necessarily follow this outline, as the material at hand often determines the method of procedure. Most of these suggestions apply to a producing field where wells are being drilled and where few or no data have been collected. Even where there is no active drilling many of the suggestions are applicable. It is not always possible to use all of the suggestions in every oil field.

1. Prepare field maps showing the elevation and location of all wells.

2. Assemble all drilling and redrilling records, daily well reports, production records of oil and water, tubing depths, fluid levels, and other data for the purpose of compiling a complete log and history for each individual well. This log should contain in addition to the formation record a chronological history of each piece of work on the well, such as redrilling, deepening, perforating, or plugging, and also a description of all tests and important features, such as bailing or pumping tests.

3. Review the histories of abandoned wells.

4. Study data on the drilling and behavior of neighboring wells.

5. Collect and compile individual well records showing monthly production of oil and water and prepare these graphically.

6. Collect samples of the formations, water, and oil from drilling and producing wells.

7. Present underground conditions graphically by means of cross sections, underground structure-contour maps, convergence maps, peg models, stereograms, and miscellaneous graphic plots. In the plotting of cross sections the most important features relating to correlation and production of oil and water should be emphasized and in correlating the strata or formation shown in cross sections and peg models an attempt should be made to find a marker or key-bed, that is, some formation easily identified in the wells.

PREPARATION OF FIELD MAPS.

LOCATION AND ELEVATION OF WELLS.

Before the engineer can proceed with the preparation of cross sections it is necessary for him to know the location and elevation of each well. These may be indicated on maps. Rapid and sufficiently accurate work can be accomplished by the use of a transit or plane table and stadia rod, one survey giving both the location and elevation of the wells.

The survey should determine by direct reading or computation the location of the center of the hole—not of one corner of the derrick. In field practice the wells are usually located by reference to established surveys or to known corners or lines of sections or tracts. Location should be correct within a few feet. Where possible it is advisable to locate the wells according to Government surveys, as these are usually the basic and binding surveys for land ownership. Wells are sometimes located with reference to a near-by well.

The elevation of the wells should be in reference to an established datum, preferably a bench mark of the United States Geological Survey. Elevation should be correct within at least 2 feet, and

preferably 1 foot. If there are no bench marks in the immediate neighborhood and if the work is "rush," the elevations may be based on an assumed datum. The recorded elevation should be that of the derrick floor, as-hole measurements are generally referred to the derrick floor as a base. Where no derrick is standing, the surveyor should take some point that is constant for all wells, as 2 feet above the ground level or the top of the casing, for it is desirable to obtain the elevation of the zero point from which the well measurements were taken.

Well elevations may be correctly obtained by use of the level. The aneroid barometer has been used for determining well elevations, but in using an aneroid its readings should be corrected against known elevations several times during the day. The hand level and the Brunton compass have also been used in obtaining well elevations. With these the observer stands on a known elevation and looks into the superstructure of the derrick; then by counting the girts and taking account of the distance between them and knowing the height of the observer, the elevation of the derrick floor may be computed.

The use of the aneroid, hand level, and Brunton compass is not to be recommended, but an elevation known to be reliable within certain limits is better than no elevation or even one from an unchecked source.

FIELD MAPS.

It is not the purpose of this paper to discuss means of surveying, field engineering or field maps,¹ but there are two maps of particular use in underground work and these maps will be briefly discussed.

In the preparation of cross sections it often happens the exact distance between different wells has not been computed, particularly if their location has been determined by the stadia method. After a stadia survey, the wells can be plotted on a map with a scale of about 400 or 500 feet to the inch and then in the preparation of cross sections the distance between the wells can be determined by a scale. The horizontal distances of a stadia survey are not always correct to within 4 or 5 feet, so the wells can be plotted on a map with a scale of 500 feet to the inch about as accurately as the results of the survey. Hence when the stadia method is used it would seem that a 500-foot scale is sufficiently accurate for future scaling in the preparation of cross sections. When the well distances have been computed it is, of course, simpler to have the distances recorded as in figure 1. The elevation of each well can be plotted with ink of distinctive color on this map beside the well number.

¹ R. T. Wells has described the value of oil-field maps in the Doherty News, January, 1919.

35

California
Consolidated
Oil Co.

Midway



36

Oil Co.

Midway
O. Co.

Symbols may be used to show the status of each well; that is, a different symbol designates whether a well is drilling, redrilling, producing oil, producing gas, producing oil and gas, producing water, or abandoned. It is readily evident that in an active field the status of the wells is constantly changing, hence the symbols must be revised at regular intervals. Well symbols should allow progression from rig to abandonment with as little erasing as possible. A set of symbols is shown in Plate I, under the heading "Legend."

PROGRESS MAPS.

USE OF PINS.

On a wall map the pin system can be used to show the general conditions of the property. The map should be mounted on a soft background into which a needle-point pin can be pushed. Pins with various colored spherical glass heads and pins with numbered cloth heads or numbered celluloid heads can be used on a wall map, similar to Plate I, to designate the status of the wells. For example, colored pins serve to show whether a well is drilling or abandoned. It is important that on all maps the same color be used for the same purpose, so that the operator may recognize readily the meaning of each pin. The pins should be changed regularly with each change in the condition of the well.

A producing well is the normal thing to expect, so no pin is used for it, the solid black circle on the print being enough. Drilling wells may be represented by a yellow pin, redrilling by orange, abandoned by black, oil wells making a slight amount of water by green, and oil wells making a serious amount of water by red, etc. On another map colored pins may be used to show the water content of different wells, those making 10 barrels of water or under being designated by a yellow pin, 10 to 50 barrels of water by a green pin, over 50 barrels of water by a red pin.

If a photograph is desired, a map printed in certain colors does not photograph in black, and pins of a properly selected color show up distinctly on the light background in contrast to the light section lines or the color showing property ownerships and other details.

Pins in common use are one-half inch long, with a round bright-colored glass head about one-half the size of a pea. They can generally be purchased from stationery stores.

ASSEMBLING OF DATA AND COMPILATION OF A WELL LOG.

Before any constructive work on an underground problem can be accomplished the old records of wells should be reviewed. This

review necessitates the collection of all books, records, and other data giving information on the wells. Such data naturally include well-drilling books, office drilling records, drillers' tour reports, drillers' notebooks, redrilling books, production reports, tubing records, fluid levels, and in fact all information that deals with the work on or condition of a well at any time, and particularly any tests of the well. The verbal statements of drillers should be noted.

Old records are awkward to use unless they have been compiled into convenient and accessible form; hence after these records have been collected the next step is to arrange them in a form for ready reference. (See discussion on Forms, pp. 201 to 229.) Where the records are not clear, the foremen and drillers should be consulted freely. Any information such as "sulphur smell," "found salt water in bailer," or "fluid rose in hole" should be noted on the log. The top and bottom of lost casing or tools should be recorded. The engineer soon learns to distinguish between the important and unimportant features and should, of course, record only the important. The well log record has developed as a matter of convenience because it brings together in concise, compact form the data relative to a well so that whenever a well is discussed its complete history is available.

Form 1 is a practical type of well log adapted to California requirements. The method used to file and designate each well is important. This information, that is, the field, the name of the company, and the well number is recorded on the upper part of the face of the log. The logs may be filed numerically by section and tract.

The most important features should be emphasized on the log, so that they will be readily discernible. For example, in the original record reproduced in Form 1, the well number and section (by which the wells are designated in the Coalinga field) were shown in red (represented here by the black bold-face type); indications or showings of oil and gas were shown in red; water at 797 to 805 feet and 1,608 to 1,620 feet was typed in capital letters; the level of the water at 797 to 805 feet was known and was recorded on the face of the log. The depth of the casing is recorded opposite the formation in which it is landed.

Color and hardness of each formation should be noted as well as the occurrence of pyrite, sea shells, limestone, "hard shell," or "sulphur smell." It is important to know the location of any peculiar or particular features that may cause trouble in the well or in adjoining wells, such as a "running sand," or "cavey formation." This can be recorded under the description of the formation.

FORM 1.—Specimen well-log record.^aFIELD *Coalinga*

(FRONT SIDE.)

COMPANY

*California Oilfields, Limited
(Shell Co., of California)*

LOG OF WELL No. 78

DESCRIPTION OF PROPERTY (Quarter Section) S. W. $\frac{1}{4}$ of Sec. 27, 19/15

LOCATION OF WELL 740' N. and 2905' W. of S. E. corner

ELEVATION ABOVE SEA LEVEL 1178 Feet

COMMENCED DRILLING Oct. 29, 1913. FINISHED DRILLING—See History

Depth from—	To—	Feet.	Formation.
0	10	10	Brown adobe.
10	25	15	Brown sand.
25	55	30	Yellow clay.
55	65	10	Coarse gray sand.
65	98	33	Black gravel.
98	125	27	Brown sand.
125	185	60	Blue sandy shale.
185	210	25	Light blue shale.
210	245	35	Coarse gray sand.
245	315	70	Light blue shale.
315	317	2	Brown shale.
317	330	13	Blue shale.
330	390	60	Sandy blue shale.
390	404	14	Fine gray sand.
404	440	36	Light green shale.
440	450	10	Gray sand.
450	478	28	Coarse gray sand and gravel.
478	497	19	Gray sandy shale.
497	510	13	Coarse gray sand.
510	555	25	Sandy blue shale.
555	580	45	Blue shale.
580	640	60	Sandy blue shale.
640	690	50	Gray sand, shows tar oil.
690	705	15	Blue shale.
705	715	10	Sandy blue shale.
715	723	8	Gray sand, shows tar oil.
723	753	10	Fine hard gray sand.
753	740	7	Hard sand shell.
740	753	13	Gray sand, shows tar oil.
753	757	4	Blue sand shell.
757	785	28	Soft gray sand.
785	796	11	Blue shale.
796	797	1	Hard sand shell.
797	805	9	Soft sand and gravel, Water. (Water stands at 600'.)
805	806	1	Hard sand shell.
806	870	64	Sticky blue shale.
870	905	55	Fine gray sand.
905	920	15	White sand and sea shells. (Put in 2 loads red mud at about 930'.)
920	965	45	Soft gray sand.
965	985	20	Sandy blue shale.
985	1,005	20	Sandy shale, black.
1,005	1,055	50	Fine soft gray sand.
1,055	1,092	37	Hard coarse gray sand.
1,092	1,104	12	Sticky black shale.
1,104	1,129	25	Sticky light blue shale.
1,129	1,140	11	Light gray slate.
1,140	1,214	74	Tough green shale. (12½" casing cemented at 1214'.)
1,214	1,232	18	Tough, sticky green shale.
1,232	1,280	48	Light green shale.
1,280	1,295	15	Light blue shale.
1,295	1,305	10	Light gray shell.
1,305	1,330	25	Sticky blue shale.
1,330	1,348	18	HARD GRAY OIL SAND, fair
1,348	1,363	15	FINE GRAY OIL SAND, good.
1,363	1,380	17	Hard gray sand, no oil.
1,380	1,393	13	SOFT GRAY OIL SAND.
1,393	1,410	17	Hard gray sand, no oil.
1,410	1,421	11	Black sandy shale.
1,421	1,423	2	Hard sand shell.
1,423	1,440	17	Fine black sand.
1,440	1,445	5	Hard sand shell.
1,445	1,470	25	Fine dark gray sand.
1,470	1,493	23	Sandy blue shale. (10" casing cemented at 1426'.)
1,493	1,495	2	Hard sand shell.
1,495	1,500	5	Very sandy shale, shows oil and gas.
1,500	1,510	10	Soft fine gray sand, shows oil.
1,510	1,525	15	Light blue shale.
1,525	1,587	62	Gray sand, shows oil and gas.
1,587	1,598	11	Black sandy shale.
1,598	1,608	10	Hard fine gray sand, no oil.
1,608	1,620	12	Fine black sand, shows Sulphur Water.
1,620	1,629	9	Tough black shale.

^a Original, 8½ by 21½ inches in size.

(Reverse side.)

(LOG CONTINUED.)

HISTORY OF ORIGINAL DRILLING.

Casing f. oze at 1358'. Bailed to free the 10" casing and bailed dry. No record concerning water (12/15/13). Put in red mud, drilled ahead, finding 50'. Cavings in hole (12/16-18/13).

10" casing cemented at 1497' with 56 sacks cement dumped in (12/24/13). Cement 10' in casing, but bailed out 5'. Cement set to Mar. 18, 1914. Bailed hole dry, stood 6 hours and made no water. Drilled pocket to 1517', bailed hole dry, stood overnight and made 2 pails of water and a little oil. Then started to put in 8 1/2" casing. Drilled hole to 1680'; well showed evidence of sulphur water.

8 1/2" casing. Had in 1581' of 8 1/2" casing and then pulled two joints and bailed hole dry, stood 5 hours, and made 168' of water and no oil. Bailed hole dry and sand filled hole up to 1550'. Bailed at 1-hour intervals and well made 5 bailers (6 1/2" by 40") each run of black water, "smelling strongly of sulphuretted hydrogen. There is also a little oil" (5/24/14).

Bailed, hole made 5 bailers per hour of water with a little tar oil. Made 10 bailers after standing 2 hours (3/25/14). Bailed hole, made 5 bailers per hour of black sulphur water with a little tar oil (3/26/14). Bailed; no change in quantity of water or oil (3/27-30/14).

Pulled so as to loosen 10" casing and cement it lower in order to shut off sulphur water (3/31/14).

10" casing. Got 10" vibration at 1425'. Filled hole from 1501' to 1497' with brick and cement. Put in 5 sacks cement and drove two wooden plugs into cement, top of plugs at 1490'. Dumped in 10 sacks cement and drove two wooden plugs, filling hole to 1462'.

Ripped 1425' to 1455' and filled hole to 1385' with 19 sacks cement, broken concrete, M. & F. plugs. Dumped in wheelbarrow load of gravel and ripped 10" casing at 1345' to 1370'. Put in 4 sacks cement, filling hole to 1365'.

Pulled 1358' (4/11/14), left 162'. 1335' to 1497' to be cased off. Drilled to 1395' and found tools following old hole. Filled to 1370' with bricks and 8" by 8" timbers, then drilled past casing to 1629'. Reamed to 1626'.

10" casing cemented at 1626' (4/29/14) with 73 sacks cement dumped in. Ran in and found cement 10' up in casing. Shut down for cement to set. Idle until August 23, 1916.

HISTORY OF PLUGGING AND PERFORATING.

10" casing. Drilled pocket to 1630' (8/25/16). Bailed dry at 3-hour intervals.) Made 3 1/2 barrels of water per hour. Tested by bailing from Sept. 30, 1916, to Oct. 1, 1916. Made 2 1/2 barrels of water per hour.

Plugged to 1587' feet with 50 sacks cement, Sept. 2, 1916. Perforated by machine as follows: 1330-1410; 1423-1470; 1529-1580.

Bailed. Made 29 barrels of oil in 24 hours. Small show of water, Sept. 15, 1916. Tubed at 1480' with 3" tubing Sept. 30, 1916.

Production. About 40 b/d and no water. Gravity 25.3.

CASING RECORD.

15 1/2 in. landed at 834 ft., cut at (All Pulled) ft., weighing 70 lbs. brand DBX (11/17/13)

12 1/2 in. cemented at 1214 ft., cut at ft., weighing 40 lbs. brand DBX (12/3/13)

10 in. cemented at 1626 ft., cut at ft., weighing 48 lbs. brand DBX (4/29/14)

OIL AND GAS SANDS.

From 640 ft. to 690 ft.	From 1380 ft. to 1393 ft.
From 715 ft. to 723 ft.	From 1500 ft. to 1510 ft.
From 740 ft. to 753 ft.	From 1525 ft. to 1537 ft.

WATER SANDS.

From 797 ft. to 805 ft.	Water stands at 600 ft.
From 1620 ft. to 1603 ft.	

METHOD OF SHUTTING OFF WATER.

12 1/2 in. casing cemented at 1214 ft. with 31 sacks of GG (12/3/13) cement.

10 in. casing cemented at 1497 ft. with 56 sacks of dumped in (12/24/13) cement.

10 in. casing cemented at 1626 ft. with 73 sacks of dumped in (4/29/14) cement.

From -----

WATER TESTS.

(State how long cemented. Water level. Details of bailing and results.)

12 1/2" casing. Practically no cement in casing. Cemented at 1214' (12/3/13). Set until 12/7. No record of any test.

10" casing cemented at 1497' with 56 sacks cement dumped in (12/24/13). Cement 10' in casing, but bailed out 5'. Let cement set to 3/16/14. Bailed hole dry, stood 6 hours and made no water. Drilled pocket to 1517', bailed hole dry, stood overnight and made 2 pails of water and a little oil.

10" casing cemented at 1626' with 73 sacks cement dumped in (4/29/14). Ran in and found cement 10' up in casing. Shut down for cement to set.

PERFORATIONS.

Machine From.	To:	Rows.	×	Holes per foot.	See History.
-----	-----	-----	-----	-----	-----
-----	-----	-----	-----	-----	-----
-----	-----	-----	-----	-----	-----

Gravity of oil 25.3 Water cut 0
 Date well began prod. Sept. 30, 1916.
 Remarks: (Special features not provided for above)

At a depth of
 Drillers.
 Harper, Brandle, Wheat.

Feet

A log should present a complete history of a well from the time drilling starts until the well is abandoned. The history of the work should be arranged according to dates, each job set off by itself. (See "reverse side" of Form 1.) This allows the work on the well to be followed step by step and makes easier the comparison of the various tests.

The history itself should contain a complete and full record of all available data on the underground features of the well, and should disclose the status of the well at all times since drilling started. When a well is producing normally, this fact is shown by the production record.

Drilling the well provides the first part of the history, and the bulk of this information is furnished by the driller's report. The production of oil and water should be recorded occasionally throughout the history, particularly after any repair work. Any casing, drilling tools, lugs, or bailers, cased off in the hole, may cause future trouble, and it is well to know the depth at which they were side-tracked. Each factor that may indicate the presence of an oil, gas, or water sand should be recorded. Water tests should be given in detail. If a well was bailed, the depth to which the fluid was bailed, the hours the well stood, the results of the test, or, in case of cementing, the whole time from the mixing of the cement until it was placed behind the pipe and the casing seated, are all important and should be recorded. A great deal of the data discussed under "Driller's tour report," on pages 201 to 207, should be noted. With a little experience in the field the important facts for record are soon recognized.

At the lower half of the back of Form 1 space is provided for information on the casing record, oil and gas sands, water sands, method of shutting off water, water tests, perforations, initial rating,² gravity of oil, and names of drillers. In many fields the well log record should provide for information on shooting a well; that is, the depth at which it was shot, the number of quarts used, and the results of shooting.

REVIEW OF HISTORIES OF ABANDONED WELLS.

In going over the well data, plotting logs, and correlating cross sections the engineer should not neglect old abandoned wells. A complete history of such wells should be worked up and plotted with the other well logs. These histories should be studied for the purpose of learning the present conditions of the wells and to see whether they may be letting water into the oil formations. Where no records of such wells are available, the engineer should, if possible, confer

² Some companies record for the initial rating, the production for the first month, or for the first 24 hours, or for 24 hours after the well has produced 30 days.

with drillers of the wells and find out the condition of each well when abandoned and record the information for future reference.

A great number of abandoned wells have been carelessly plugged, as very often the object on abandonment is to reclaim all casing as quickly as possible and forget the troubles occasioned by the well. As a result, some abandoned wells have caused much harm by allowing water free access to the oil sands, and operators have had to go back later and plug such wells.

Upon abandonment a well should be plugged properly and care should be taken to confine the water to its original sand, either by cement³ or by the use of mud-laden fluid.⁴

When an old well is found to have been improperly plugged, and to be flooding the oil sands with water, this fact should be called to the attention of the superintendent at once, and recommendations made for repair.

STUDY ON DRILLING AND BEHAVIOR OF NEIGHBORING WELLS.

In working up the account of the underground conditions at a property, the neighboring wells should be carefully studied, for, obviously, property lines do not affect geologic facts. Cross sections, particularly of adjoining wells, should be made, and their casing depths and histories carefully reviewed in order to obtain the same information as for the company wells.

The neighbor's method of drilling and producing from his wells may differ considerably from that of the operator in question. Perhaps such study will indicate that the neighbor is getting a larger production per well because he is producing from a sand overlooked by the operator. The neighbor may have tested an upper sand and found it nonoil yielding. This knowledge will save an expensive similar test on adjoining properties.

It is human to blame a neighbor for an undesirable condition in a well or group of wells. However, an open-minded study of conditions often not only shows the operator that one of his own wells is at fault but gives him information of distinct advantage in operating his own property.

For these reasons, for the purpose of saving unnecessary expenditures and unnecessary material for testing, and for better protection against water, there should be a complete exchange of well data, particularly on line wells, between neighboring companies. It has been proved many times that the exchange of information is bene-

³ Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163. Bureau of Mines, 1918.

⁴ Lewis, J. O., and McMurray, W. F., The use of mud-laden fluid in oil and gas wells: Bull. 134, Bureau of Mines, 1916, p. 46.

ficial to both sides and a frank comparison of information may yield valuable results. Great good can be gained through cooperation and the day of secrecy in the production of oil has passed.

COLLECTION AND COMPILATION OF INDIVIDUAL WELL PRODUCTION RECORDS.

The production record of oil and water from each well should be collected and compiled in convenient form after the manner discussed on pages 219 to 222 under "Yearly Summary of Monthly Productions." Although it may involve considerable work, the future convenience and knowledge gained from a study of such records will more than offset the cost and trouble.

Forms for the daily individual well production (see Form 14, p. 215 and the monthly individual well production (see Form 16, p. 218) should be prepared and arrangements made to collect the necessary data. If no individual well gages are being taken some system of gaging should be adopted immediately. (See pp. 178 and 179, "Importance of gaging.") If no old records are available the pumpers and foremen should be questioned regarding each well's past record and any seemingly trustworthy information should be recorded with an explanatory note as to its source. Where there are no records of individual well production, the production from a group of wells should be compiled and plotted, if such monthly figures are available.

PLOTTING OF PRODUCTION RECORDS.

After the old data have been compiled, the production curves of oil and water should be plotted on coordinate paper. Usually the monthly production of oil and water is best to plot, but if a well is under close observation the daily output may be plotted. Plate X (p. 58) is an example of such a plot, which can be readily made on a form having the days of the month printed on it. These curves show at a glance any sudden or gradual increase of oil and water and form a fair idea of the well's future. (See fig. 2.)

This figure shows the gaged oil production of the well each month. Until May, 1914, the percentage of water was determined by centrifuge tests of samples of fluid taken from the lead line, and the water production in barrels was computed from the percentage of water as determined by the centrifuge test and by the corresponding monthly production of oil. The total fluid produced after May, 1914, was fairly constant, probably because the well produced all that the pump would handle. A larger pump would probably have produced more water, as the pump was a considerable distance off bottom and the oil produced was that skimmed off the water. All

of the time, however, water filled the hole between the pump and the bottom of the hole and was probably working back into the

oil sands. This particular well made a serious amount of water from the time it came in.

Any changes in the gravity of the oil were recorded on the curve at the date the difference in gravity was found, the gravity for each month up to that point being the same as the last gravity recorded.

One of the many advantages in plotting production records is shown in figure 3. The individual well production-curves of this property were plotted a year after the tools were lost in the hole. A sudden decrease in production was noted but no explanation for the decline could be found in the records. A new management had taken charge of the property during the interim between the loss of the tools and the plotting of the records. The production foreman recalled that in cleaning out the well in July, 1915, a string of tools was left in the hole. When this fact

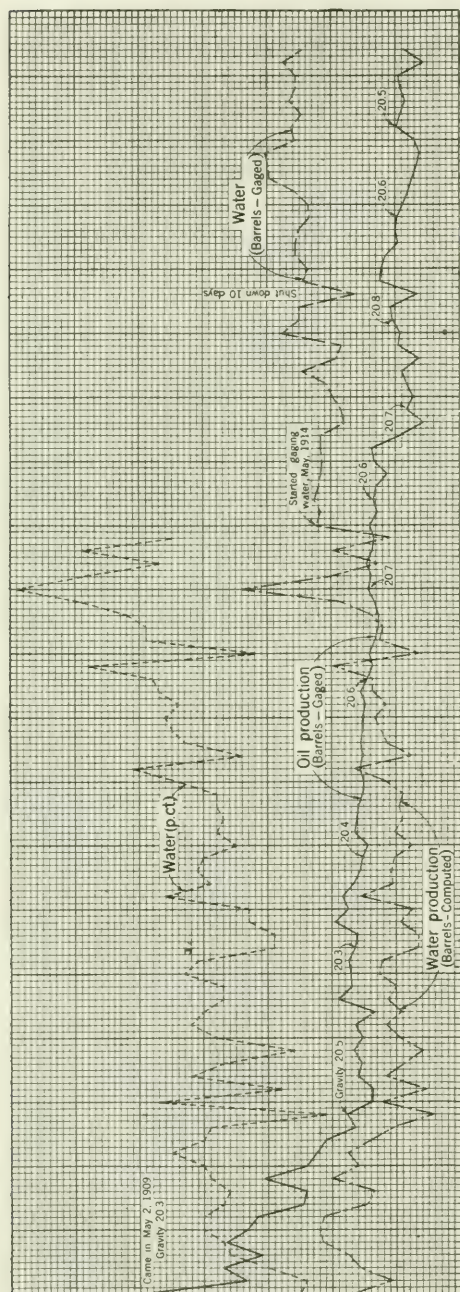


FIGURE 2.—Plot showing well production of oil and water. Until May, 1914, the water production was determined by a centrifuge test of a lead-line sample. The actual water production up to that time was computed and is shown in the figure. After May, 1914, the water production was gaged.

was ascertained a crew was directed to fish out the tools, but unfortunately the pipe was so crooked that the top of the tools could not be

reached. Had the pipe not gone bad, it is likely that the company could have jarred out the tools and increased the production from 40 barrels a day to the old figure of about 140 barrels a day. There was particular need of keeping up the output of this well, as the well was near the property line and the neighboring offset well was probably recovering the lost production. But for the pipe having gone crooked, the plotting of production records would possibly have resulted in a fishing job leading to increased production. Furthermore the incident showed the necessity of close contact with the production foreman.

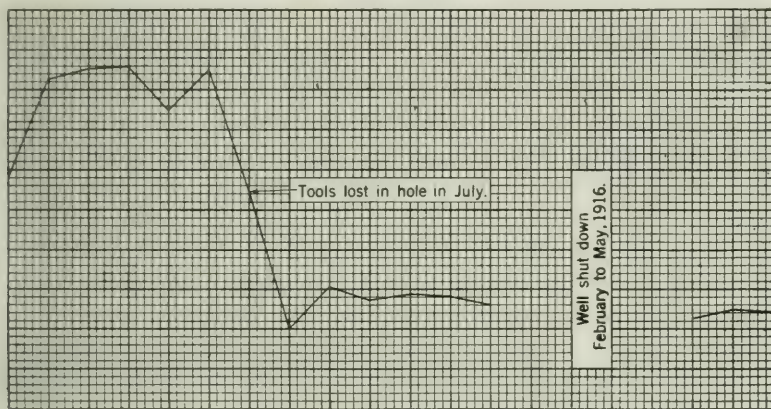


FIGURE 3.—Plot showing how tools lost in the hole decreased the oil production. The well history did not show any lost tools, but the production curve indicated some trouble. Upon inquiry of the production foreman, it was learned that the tools were lost in the hole at the time of the sharp decline in production. See text.

COLLECTION OF SAMPLES OF FORMATIONS OF WATER AND OF OIL.

NECESSITY FOR TESTING A DRILLING WELL.

It is highly important that a well be drilled in such a manner as to furnish definite information on the possibilities of the area. A wild-cat well, in particular, is drilled for information, and so much money is involved in drilling that the most should be made of the expenditure. There is often a tendency to look for gushers only, but it is folly to try to save a few dollars by not testing every likely oil-producing formation. The engineer should collect samples of the formation and oil or water. The collection of water samples is discussed under "Water analyses," on pages 88 to 90. An oil sample for analysis can be collected only when the showing is very good. Formation sampling is discussed on the following pages.

Goodrich⁵ points out that several thousand dollars are tied up in a well, and, therefore, the operator should exert every effort to gain

⁵ Goodrich, H. B., Should draw drilling contracts to avoid a premium on haste: National Petroleum News, Feb. 5, 1919, pp. 58-61.

the most from his well. This same point has been emphasized by Tough.⁶

The contractor, to obtain the maximum profit, must make as much hole per day as possible, because he is usually paid by the foot. The maximum information can not be gained from a well drilled in haste, and oil companies should arrange with contractors for allowance for delays caused by sampling and testing.

PRODUCTIVE HORIZONS OVERLOOKED IN HASTY DRILLING.

Many examples can be cited of productive oil and gas horizons being overlooked, either because of improper testing or haste in getting the well down. A recent example has come to the attention of Fred H. Reusch, expert driller, of the Bureau of Mines. Near Walters, Cotton County, Okla., a well drilled by the Gladstone Oil & Gas Co., in the spring of 1918, was considered dry. A year later the Chapman well, a quarter of a mile south, came in, making 450 barrels of oil a day and much gas. The casing in the Gladstone well was then ripped for a few inches at a depth corresponding to the producing sand of the Chapman well, the result being 75 barrels of oil and 35,000,000 cubic feet of gas a day. Had this sand been properly tested during drilling the well would have been brought in much sooner. Such instances demonstrate that great care must be exercised in testing out formations, particularly in a wildcat area where one failure may prevent the drilling of other wells. -

COLLECTION OF FORMATION SAMPLES.

Samples of formations penetrated by the drill are useful in areas where the correlation of sands are in doubt: they should be collected, examined, marked, and saved for future reference. The cost of collection is very small compared with the possible ultimate value. The containers for filing the samples should be labeled to show the well number, depth, name of formation, date collected, and whether from a rotary or a cable-tool well. A convenient container is a 4-ounce glass bottle, with a tin screw top. A 2-ounce sample is ordinarily enough.

Where wells are drilled by a contractor the company should provide for the collection of formation samples. Contractors are primarily interested in making hole, and many are inclined to make hole at the expense of knowing the formation penetrated. A representative sample of each formation should be obtained and its depth ascertained: unless the depth is known the sample is of little value.

⁶ Tough, F. B., Methods of shutting of water in oil and gas wells: Bull. 163, Bureau of Mines, 1918, pp. 87-88.

Hence, where the formations are caving or running in, it is difficult to get a true sample from the bottom of the well.

The engineer should supervise the collection of the samples from the company and contract wells. To do this best he should attempt to establish friendly relations with the drillers. The drilling of a well is an art in itself and if the engineer and driller realize that each is a specialist and is working for the same purpose a bond of understanding should arise which will greatly facilitate sampling. The engineer should talk with the driller about the samples, how the formations drill, and the evidence of oil, gas, or water. The samples should be washed at the well. Eventually the driller himself will collect the samples in the manner desired.

Information thus gained often aids in the interpretation of logs and the correlation of cross sections. Hence the engineer should have his headquarters on the property where he is in constant touch with the field men and wells.

FORMATION SAMPLES FROM A CABLE-TOOL WELL.

More satisfactory samples of formations can be obtained from wells drilled with cable tools than with rotary, because there is usually less open hole which precludes cavings, and the tools are pulled out oftener.

The bit should be closely observed when it is pulled from the hole as some formations wear the bit and others do not. Sand wears the bit smooth and shiny and it comes out of the hole clean. Shale and clay wear the bit very little and generally stick to it when it is drawn from the hole. Samples of sand can be obtained from the bailer after the upper part of the drilled material, which may contain cavings, has been bailed out and the bailer run to near bottom.

After a sample of sand has been collected from the bailer, the sand should be placed in a bucket, the nozzle of the hose placed on the bottom of the bucket, and a slow stream of water turned on to float out the mud. Hot water seems to show up oil colors better than cold water.

The engineer should note whether the sand is fine, medium, or coarse grained, its color and other properties, such as whether it is angular or round, predominantly quartzose, etc. Any evidences of sea shells, pyrite, salt, alkaline or sulphur water, salt or gypsum crystals, limestones, marked temperature, etc., should be examined and recorded.

While collecting the samples the engineer should learn from the driller whether the formation drills hard, is sticky, tough, cavey, etc. Color should be observed, for although it is not always persistent, still certain formations have a persistent color over a consider-

able area, for instance, the Permian Red Beds of the Mid-Continent fields.

If clay or shale sticks to the side of a bit, a sample should be collected, examined, and filed in the container.

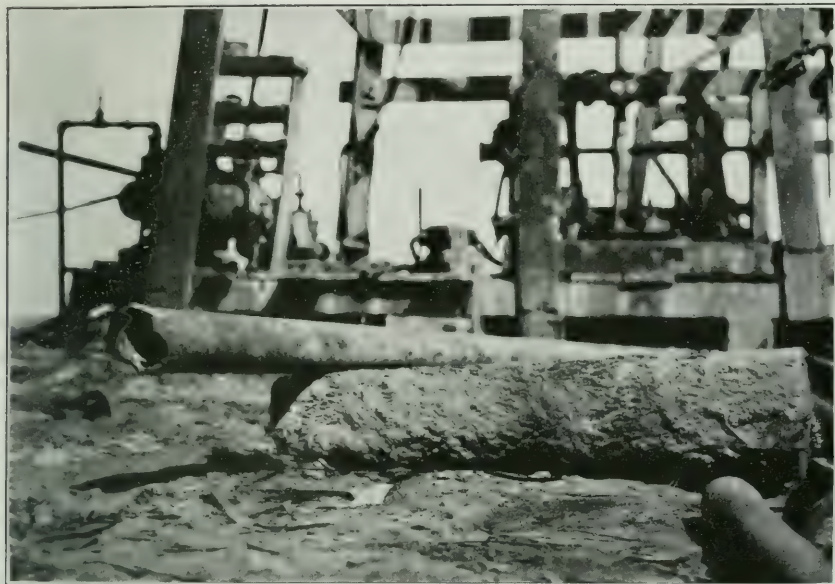
Limestone is sometimes persistent in the Mid-Continent field, as is the Pittsburgh coal in the Appalachian fields. The occurrence of either limestone or coal deserves special attention as a probable marker or key bed. Large fragments of these should be collected from the bailings for examination.

FORMATION SAMPLES FROM A ROTARY WELL.

Rotary drilled wells are generally much more difficult to obtain samples from, and hence furnish less trustworthy logs. Sometimes a sticky shale or clay will cling to a rotary bit as it is pulled from the hole, but often the bit will drill 100 feet without being pulled, then the only material available for sampling is the pumpings from the ditch. Such samples are unsatisfactory because the returns may contain cavings from another formation and because of the uncertainty of estimating the time required for the returns to reach the surface. This difficulty of getting reliable logs, in addition to the fact that the heavy fluid of a rotary holds back oil and gas showings, has caused objections to drilling wildcat wells with rotary rigs.

In the past, cable-tool well logs have been on the whole much more accurate than rotary well logs, causing a more or less popular distrust in the latter. Rotaries are valuable because they make hole fast, hence the drillers tend to give less care to the formations. One of the real reasons why rotary logs have been so unreliable in the past is the failure to realize the value of good records. Of course, cable-tool logs are more reliable, but formations can be determined fairly accurately with a rotary if proper observation and care is made during the drilling. Hard rock, hard "shell," sand (hard or soft), shale and gumbo, can usually be detected by watching the way the engine runs, the action of the rotary table, the "tune" of the mud pump, and the way the bit wears.

There are many examples where formations can be detected by the way they drill. In the Caddo oil field, Louisiana, the Nacatoch sand usually drills very hard, wears out many bits and drills quite differently from the formations immediately above and below. Most drillers of that area can tell when they reach the Nacatoch sand. In other areas a hard limestone "shell" causes the rotary drill stem to jump and catch, and in this limestone the drill will make hole slowly. Again, gumbo will cause the bit to "ball up," necessitating an occasional spudding to clean the bit. Where such formations are persistent over a considerable area, they are of material aid in the correlation of rotary logs.



A. IMPROVISED ROTARY CORE BARREL.

(Courtesy of W. W. Scott.)



B. CLOSE UP VIEW OF IMPROVISED ROTARY CORE
BARREL.

ROTARY CORE BARREL.

The use of a core barrel or drag shoe in sampling formations in a rotary well gives much more satisfactory results. Core samples are obtained at a sacrifice of speed in making hole, but in wildcat territory the loss of time is thoroughly justified, because such samples supply accurate data, which is essential for determining the local position of the oil horizons and for differentiating between formations which aid in drilling and future correlation.

Very satisfactory work can be done with a rotary when taking cores, and there is no reason for not obtaining good samples as often as may be necessary to determine completely all of the geologic formations. An experience of H. L. Hamilton, consulting petroleum engineer, Houston, Tex., is cited as an example. He directed the drilling of two rotary wildcat wells in northern Louisiana. In the first well no core barrel was used and the well was stopped on reaching what was supposed to be the Woodbine sand, the main producing sand of the Caddo oil field. In the second well, which is close to the first well, a core barrel was used, and good fossils were obtained which showed that the bottom of the first well was actually several hundred feet above the Woodbine sand. In this work the value of the data obtained with the core barrel obviously more than justified its use.

Core barrels can be obtained from the larger oil-well supply houses, or one can be improvised from an old piece of casing by sawing teeth in one end and bending them to the desired "set." The barrel is screwed onto the bottom of the drill stem in place of the bit. W. W. Scott, in charge of a core-sampling job for Mr. Hamilton, in northern Louisiana, describes⁷ the tool (see Pl. II, *A* and *B*) they used as follows:

The core barrel that we have used is very simple and effective, especially in the Lower Tertiary and Upper Cretaceous formations in the South. We have taken cores from 30 feet to as deep as 3,300 feet with core barrels made from ordinary 8-inch, 6-inch, 4-inch, and 3-inch pipe. We seemed to get better results with 6-inch and 4-inch casing of ordinary weight. If the samples are for geological purposes, the larger the better; but if for determination of formations, a small core is sufficient. Teeth can be cut in an ordinary joint with a hacksaw. In 6-inch pipe we usually cut six teeth and in 4-inch and 3-inch pipe about four teeth. Every other tooth is bent in slightly, and the others are bent out slightly. The teeth bent in make a core smaller than the inside of the pipe, and the teeth bent out make a hole larger than the pipe which facilitates taking a long core—that is, you must have clearance for mud returns. It is essential to have holes in the core barrel to let the fluid out when the pipe is pulled.

Usually we can cut and capture the core in the same run. A core barrel must be run with very little weight on it or the teeth will turn in. After

⁷ Personal communication.

the core is cut, the pipe should be spudded or the core barrel rotated with the weight of the pipe on it in order to detach and recover the core.

In sandy shale, shale, and gumbo it is comparatively easy to cut and catch a core in the same run. After cutting the core, it is detached by rotating the pipe without circulation. This seals the bottom and holds the core in the pipe and tends to detach it. To catch a sand core, it usually takes rotating with the weight of the pipe resting on bottom, or spudding so as to bend in the teeth.

Copies of various patents for obtaining core samples may be obtained for 5 cents each by addressing the Commissioner of Patents, Washington, D. C.

Regardless of the method used, rotary or cable, the engineer should attempt to collect all available information on the formations and where possible obtain samples. He should also realize that samples can be obtained best when working in friendly harmony with the drillers.

TESTING SAMPLES OF FORMATION FOR OIL.

Oil in a drilling well is often noticeable from a film, scum, or rainbow color of oil on the fluid bailed from a cable-tool well or on a rotary ditch. If there is little drilling water in the hole, oil will often come into the hole in quantities. It is not necessary in such cases to run a delicate test on the formation to see whether it contains oil.

In the wells of lower rock pressure gas may show as bubbles in the fluid pumped from a rotary or bailed from a cable-tool well, and is often noticed escaping from the top of the hole. At times a bailer will bubble over as it reaches the surface. This is due to the release in pressure on the fluid inside the bailer as it is withdrawn from the bottom of the well.

In the Mid-Continent field some wells are drilled with only a small quantity of water in the hole, but some wells have to be shot to make them produce, and in these the "showings" are often small.

The reader should remember that usually the pressure from the column of fluid that may fill the hole of a drilling well is greater than the rock pressure, so naturally strong oil and gas showings can not be expected. In a rotary well or in a cable-tool well being drilled with the hole full of fluid, often the oil showings are not evident and then a careful test for signs of oil may be necessary.

Where careful testing of a porous formation for oil is necessary, the method suggested by E. G. Woodruff, geologist of the Oklahoma Producing and Refining Corporation, Tulsa, Okla., for testing rock for oil by the use of chloroform or carbon tetrachloride may be used. To do this an unwashed sample of sand is placed in a small bottle, covered with one of these liquids, and the bottle corked. The bottle

should stand for 15 minutes, receiving an occasional shaking. Then the contents are filtered into a white bottom porcelain dish. If oil is present in an appreciable quantity, a dark ring will deposit on the filter paper. As a further test, the liquid may be slowly evaporated in the dish by a hot plate or the sun, but not by a flame. Oil will leave a residue in the dish.

EXAMINATION OF FORMATION SAMPLES.

Formation samples should be carefully and frequently collected in wildcat wells, in fields where there are no good markers to indicate the relative stratigraphic depth, in places where the dip of the beds is unknown, and in areas where for other reasons the correlation is in doubt.

In a developed field where the underground conditions are known, where there is a definite marker, such as the Pittsburgh coal of the Appalachian field, and the formations are regular, obviously such great care need not be exercised in the collection of samples.

In a known area a formation sample may be collected with every change of formation, if the formation is not over 50 feet thick, as the well approaches a marker or the oil sand. Examination of the samples by eye, with such observations as are mentioned on pages 11 to 15 is sufficient; the terms "gray sand," "blue shale," "limestone," etc., as determined by a casual examination and the way the formations drill, will answer.

On the other hand, where the correlation is uncertain, as in northern Texas, the collection and examination of formation samples⁸ is important. These should be collected every 5 feet. The samples should be examined carefully for fossils and fragments broken open in search of sea shells, leaf prints, plant remains, etc. Thin sections of a fragment and minute fossils may be examined under the microscope. A quantitative chemical analysis may be made of an unwashed sample.

Obviously most companies are not equipped for microscopic work, but in an unknown area the companies may combine into an association whereby each company bears its share of the expense for employing the help necessary. It may be possible for the companies to make use of the State geological surveys or universities.

The fact is that a carefully logged drilling well, in a region such as northern Texas, tells the underground story in a way that the detailed surface geology can never do; and it behooves a company to make the most of the information from the drilling well.

⁸ For detailed examination of formations, see *Some deep borings in Illinois*, by J. A. Udden: Bull. 24, Illinois State Geol. Survey, pp. 11-34; also *Aids to identification of geological formations*, by J. A. Udden: Handbook, Series No. 1, University of Texas.

GRAPHIC PRESENTATION OF UNDERGROUND CONDITIONS.

The petroleum industry has long realized the value of graphic charts and diagrams for studying various problems and for showing the relative difference between important and unimportant factors. Graphic charts are highly important in the study of underground conditions in oil fields.⁹ The uses of different types of graphic plots and diagrams and the method of their preparation are discussed in the following pages.

GRAPHIC WELL LOGS.

Graphic well logs are used in preparing cross sections and for other purposes to show graphically the formations, casing, etc., underground.

Graphic well logs should be clear and simple. To attain these points the important features should be emphasized and the unimportant omitted. In general, the most important features to be noted are the occurrence of oil, gas, and water, and the casing depths. It is always well to bear in mind that contrast of formations is desired, and to bring this contrast out all unnecessary figures and letters should be omitted so as to not detract from the main features. Clearness is also aided by sharp, decisive symbols.

SYMBOLS.

Symbols are used to designate formations of different character and to indicate whether they carry oil, gas, and water. Thus symbols are a means by which the outstanding features of any well may be quickly recognized. Those selected should be in contrast to each other, easy to recognize, and easy to plot. The same symbols should be used in all sections, as after a short study they are immediately recognized and the main features of the formations encountered can be identified at a glance. It should be borne in mind that symbols should be selected according to the prominence of a formation in the district. In short, the most easily plotted symbols should be chosen to represent the formations occurring most frequently in each locality.

The symbols used should be specially adapted to reproduction by blue printing or white printing. In general, colors are to be avoided, for when used each print must be colored to conform with the original.

The United States Geological Survey has prepared a "Chart of symbols to be used in illustrations," which represents a set that may

⁹ For a discussion of graphic methods, see "Graphic methods for presenting facts," by Willard C. Brinton. Published by the Engineering Magazine Co., New York, 1914.

serve as a guide.¹⁰ Symbols vary in each locality and are largely a matter of choice. Each company should adopt a set which is used in all of their work. It may be necessary to experiment at the start, but the most important features are soon recognized. A suggested set of symbols plotted in two ways is shown in figure 4.

The key to figure 4 is as follows:

1. Gravel or conglomerate.

2. Coarse sand producing oil.

3. Coarse sand—gas.

4. Coarse sand—tar or asphalt.

5. Fine sand—sea shells—sulphur water. On section, color sulphur water, yellow, salt water, green, etc. (Note: In general avoid colors.)

6. Brown clay with hard streaks (hard shell).

7. Black shale.

8. Gray slate.

9. Limestone.

10. White chalk.

11. Coal or lignite.

12. Sand, shows oil.

13. Sandy shale.

The key to the symbols should not be printed on the graphic well log because the symbols are supposed to indicate the formations and their contents without explanation. In figure 4 the key has been included for convenience of comparison.

In *A*, of figure 4, the formations are indicated on the left half of the plot and their contents or special description on the right half.

In *B*, of the same figure, the formation and its content are shown between the two vertical border lines and any special description is

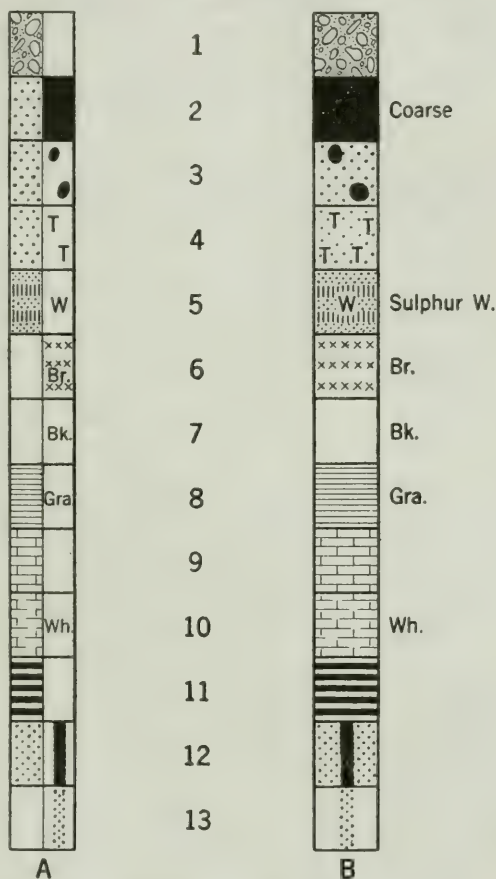


FIGURE 4.—Suggested set of symbols plotted in two ways. These are used in plotting graphic well logs. A few properly selected symbols save time in drafting.

¹⁰ See "Conventional symbols for maps and well logs": California State Mining Bureau, Bull. 82, 1918. p. 21.

noted just to the right, except in such cases as in No. 2 where the solid black, representing oil, would obscure the spacing of the dots or any lettering, then the word "coarse" is shown on the right. In No. 4, "T" represents tar, and in No. 5, "S. W." could be shown inside the two vertical lines if it would not be confused with the symbols for sea shells. A system of plotting similar to *B* is preferable as the formations stand out better, which makes correlating easier.

In the selection of symbols it is generally recognized that there are certain standard symbols used for sand, shale, limestone, and chalk, also that a producing oil zone is usually represented by solid black. These customary symbols are shown in figure 4, excepting that for shale. For uniformity, it is best to use these recognized symbols except in certain cases.

The customary symbol for shale is a series of dashed horizontal lines. In most fields the bulk of the formations encountered in the drilling of wells is shale or clay. When brought to the surface the drillings have often been so crushed or churned by the bit that it is difficult to tell whether they are clay or shale. One driller may call the formation shale while another will name it clay. Clay and shale may both be left blank, thereby saving a great deal of a draftsman's time. Furthermore, the blank space for shale and clay contrasts with the symbols of other formations and is, therefore, satisfactory for correlating purposes. For that reason the writer does not advocate the ordinary use of the standard symbol for shale.

Symbols are given in figure 4 to represent conglomerate or gravel, coarse or fine sands, oil, gas, tar, asphalt, sea shells, shale, clay, hard shells or hard streaks, slate, limestone, chalk, coal or lignite, and sandy shale. In certain localities other symbols are often necessary, and some of these may not be needed. Coarse or fine sand is distinguished by the difference in spacing and size of dots. If a little care is exercised in plotting there is no need to print the words "Coarse" or "Fine" at the side (unless the contents of the sand as in symbol 2, of *B*, obscure the spacing of the dots). Sea shells are shown by vertical parallel lines. Water should be given special consideration. It may be emphasized by coloring¹¹ the log as well as printing the word "water" opposite the formation in which it occurs. Hard shells are represented by small crosses. In this suggested set of symbols, slate has been given a separate symbol. Slate often serves as a marker for it is generally recognized by the driller on account of the flinty chips that come to the surface and by the way it drills. The slate is often of uniform thickness and generally occurs over a considerable area. The symbols for limestone, chalk, and coal or lignite need no explanation.

¹¹ The use of colors should be avoided, if possible, although colors tend to emphasize differences, each print must be colored to correspond. This takes time and labor.

Sand showing oil may be indicated by an irregular heavy ink line, as No. 12, figure 4, which symbol is in contrast to the producing oil sand, No. 2, figure 4. Similarly, sandy shale may be shown by central rows of dots, as No. 13, figure 4. Some engineers prefer to show sandy shale by leaving shale blank, as No. 7, figure 4, and printing the letters "sdy" on the graphic well log. Drillers differ on the distinction between a sandy shale and sand, or even shale and sandy shale. The dots seem to emphasize better the presence of sand.

ABBREVIATIONS.

In the preparation of graphic well logs a set of abbreviations can be adopted to expedite plotting. The same abbreviations should be used in all sections. A suggested set for colors and other characteristics that are often recorded is: Bl, blue; Bk, black; Br, brown; Wh, white; Gy, gray; Gn, green; Y, yellow; R, red; Dk, dark; Stky, sticky; Hd, hard; W. S. O., water shut off; W. N. S. O., water not shut off; Cmtl, cemented; O. S., oil sand; T, tar; A, asphalt; Sul, sulphur; Tgh, tough; and Lt, light.

SCALE USED.

The scale used in plotting graphic well logs varies with the purpose for which the plot is to be used. A scale of 100 feet to the inch has been found very serviceable for graphic logs in cross sections as well as other reference graphic logs. A scale of this size will show the formations as closely as detected by the drill and much more closely than the general accuracy of the work.

Any given length of hole or casing can be measured with an error reduced to less than 1 foot, but formation measurements made with ordinary care are, perhaps, incorrect within a few feet. With a scale of 100 feet to the inch, a maximum error of 5 feet will measure one-twentieth of an inch, and it is quite possible to plot even closer than that. Furthermore, in working from known to unknown data in the correlation of a cross section, an error may be made even greater than the amount represented by an error of 1 or 2 feet in plotting.

SPEED IN PLOTTING.

Speed in plotting graphic well logs is essential as this reduces expense and saves time. Speed in plotting can be obtained by—

1. Selecting symbols quickly plotted.
2. Leaving clay and shale or predominant formation blank.
3. Using abbreviations in plotting.
4. Not plotting the upper part of the log in a known territory, particularly if the marker or markers are within several hundred feet of the oil zone.
5. Using a graduated form which can be slipped under the tracing. (See fig. 5.)

It is not necessary to point out the saving of time by selecting symbols quickly plotted. The speed obtained by leaving clay and shale blank, and by the use of abbreviations has been discussed. Speed is also obtained by not plotting the entire log, particularly where a marker is selected near the oil horizon. (See p. 36 and fig. 7.) In drilling with a rotary, great speed is made at the top of the hole, and often the formations are not logged accurately, so there is no great need to go to the trouble of plotting them.

The writer has used a graduated scale (see fig. 5) to expedite plotting. This scale may be plotted on heavy paper. The vertical guide lines for the formations are four-tenths of an inch apart. The scale is graduated into 100-foot marks, which are in turn subdivided into 10-foot marks. This form can be used where separate strips are used for each log or where a cross section is made on a separate piece of tracing cloth. The horizontal parallel lines at the right-hand side serve as a guide in printing.

PLOTTING OF GRAPHIC WELL LOGS.

A scale of 100 feet to the inch is satisfactory for graphic logs, for, as pointed out on page 36, this scale shows a 2-foot or 3-foot change in formation. This is about as close as can be detected with the drill, except possibly where the formation is peculiarly hard, sticky, or tough.

In plotting the formations of a well record a scalar form like figure 5, drawn upon heavy paper, may be placed under the tracing cloth or paper and the vertical lines bounding the formation symbols blocked out from 0 to the scaled depth of the hole. Some logs are so plotted that the vertical lines bounding the formations become narrower as the hole reduces in size with smaller sized casings. There may be certain advantages in such a scheme, but

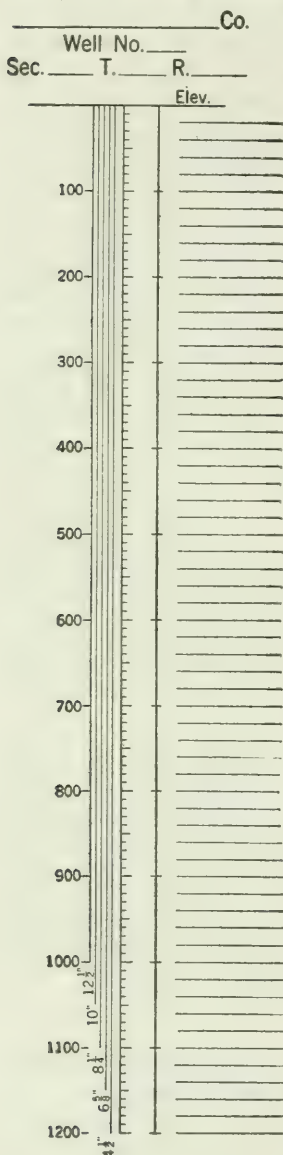


FIGURE 5.—Graduated scale used in plotting graphic well logs. This form may be drawn on heavy paper to a desired scale, usually 100 feet to 1 inch. It may be slipped under the tracing cloth to serve as a guide in plotting.

the plotting takes longer and the casing size can be shown on the left-hand side as in figure 6 (p. 33). In plotting formations on graphic well logs for making cross sections account must be taken of the datum line, (See pp. 44 to 46.)

After blocking out the log form on tracing cloth, the draftsman can see the 10-foot subdivisions through the transparent tracing cloth and with a ruling pen draw in the lines representing formation changes. These depths can be estimated to the nearest foot. The formations can be represented by the symbols as in "A" or "B" of figure 4. In A the formation is shown on the left half and the contents and description on the right half. In B the formation and contents are shown together. The writer prefers a system of plotting similar to B, as the formations stand out better, and thus B is better for correlating purposes.

Oil and gas showings should be recorded on the log. Any special features, such as a cavey formation, gas blow-out, etc., should be recorded opposite the depth denoting their location. Water should be noted in capital letters.

The writer prefers to leave off the depths indicating changes of formation, except for the more important formations or beds. Tops and bottoms of oil and gas horizons, markers, and water sands can be noted on the log, but the practice of arbitrarily recording the top of every formation should be avoided. Most of these figures are never used and they obscure important features that should be emphasized.

There are different schemes to show casing on a graphic well log, but a simple, quick way is to designate each string of pipe by a separate line, and landing depth by a horizontal line, where the size and depth are recorded. The casing can be drawn to the scaled depth where it is landed. When a string of pipe has been cemented, it may be shown by an extra-heavy line extending one-half inch above the cementing point (see well 20, in fig. 10 on p. 45), or by a fillet put in free-hand (see well 43 in Plate VI, on p. 50). Where the tests show that the casing has shut off the water this may be indicated by the abbreviation W.S.O., for water shut off.

Perforated casing or screen pipe can be indicated by dashed lines. (See perforations of 6½-inch casing in well 16, fig. 10, p. 45.)

The method of showing packers, sidetracked casing, cement plugs, and other material left underground is shown in figure 6 (p. 33), and discussed on the same page.

At the base of the graphic log may be recorded the initial and present production of oil and water, also the gravity.

Often graphic well logs are plotted on strips of coordinate tracing paper or cloth with a scale of 100 feet to the inch. The vertical lines bounding the formation symbols are blocked out and the lines representing tops of formations plotted. No such form as figure 5 is needed. The objection to graphic logs plotted on coordinate tracing paper is that the crosslines detract considerably from the main features that should be emphasized. Some companies plot the log on the side opposite to that on which the coordinate lines are ruled, and then remove the coordinate lines by the use of alcohol or chloroform. This brings out the formation symbols more clearly.

Blue prints are cheaper than blue-line prints with a white background, but the latter are much more advantageous for making notes and correlating purposes, and can be colored and worked on more readily.

HISTORICAL GRAPHIC WELL LOG.

A convenient form for presenting the history of a well in combination with a graphic representation of the work done on the well is shown in figure 6. This plot is particularly useful in wells where much testing and redrilling has been done. If a great amount of material has been left and sidetracked in the hole, its location in relation to the producing sands may be readily shown by this individual graphic plot, which brings out in consecutive order the work done on the well at different times. The history may be shown on the same sheet with the graphic drawing, then any tests made and the work on the well are more easily comprehended. This type of log is of particular value to superintendents and drilling foremen as well as engineers. It serves as a chart for discussing the work on the well.

A separate sheet is used for each well. These can be compiled on vellum paper, on letter-size sheets, $8\frac{1}{2}$ by 11 inches, which makes them easily filed and referred to. This tough tracing paper allows the use of a typewriter for typing the history. A small type (elite size) allows the history to be shown more compactly.

In the preparation of such a plot the engineer compiles the history and turns it over to a draftsman who draws in the graphic plot. The formations are plotted near the center of the sheet, the final condition of the casing is at the immediate left of the formations, the graphic representation of work to the left of this, and the detailed history at the right. With a soft pencil the draftsman indicates the figures and words to be typed, and then a stenographer may type in the history and the other data indicated in pencil.

To make the typewritten data stand out on the print the stenographer should place beneath the vellum paper a black carbon paper with the carbonized side facing the back of the vellum paper, so that the typewriter will print on both the face and back of the log.

In figure 6 only the lower 900 feet are shown, as the operator is most interested in the hole near the oil zone. If some casing should happen to be sidetracked higher up in the hole it can be shown by means of a break in the log—for example, in this log a break may be made at 1,300 feet to show any sidetracked material from, say, 800 to 1,050 feet. This can be plotted above the break.

In showing the work on the well graphically, the engineer should adopt certain symbols for cemented casing, cement, wood, brick plugs, sidetracked casing, lost tools, etc., so that all written explanation possible may be omitted. Symbols and abbreviations should be used wherever possible in all the plotting.

Each successive job is shown at the left and plotted at the corresponding horizontal depth opposite the formation.

This can be accomplished by having a ruled form

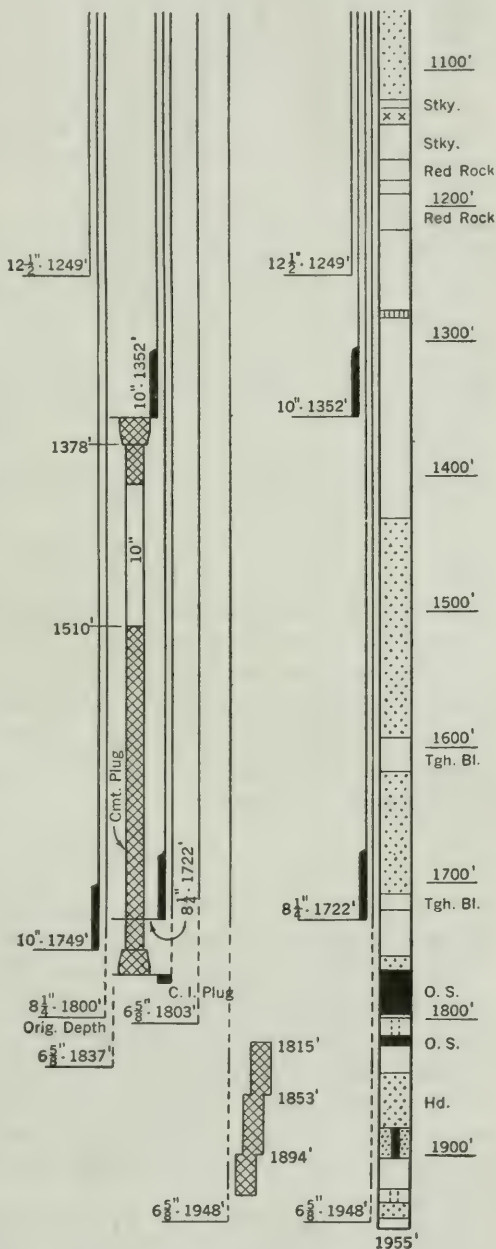


FIGURE 6.—Historical graphic well log showing history and graphic presentation of work on well on a sheet 8 1/2 by 11 inches.

underneath the paper. On this form the horizontal lines representing 10-foot and 100-foot subdivisions should extend across from the formations to the left-hand side of the log.

In the history as shown in figure 6, each job has a separate heading, emphasized by capitalization or italics—for example, Original Drilling, Deepened, Redrilled, etc., are capitalized.

Under each job, the history is subdivided according to the work done while carrying a certain size string of casing. Starting with the original drilling, a brief statement is given showing the depth of the original casing, perforations, and initial production. In this particular well, it shows the well completed April 13, 1913, at a depth of 1,800 feet. The first complete monthly production was in June, 1913, when the well made 1,372 barrels of oil, gravity 20.5, water not shown in record. The well was deepened to 1,839 feet in October, 1914. For this particular well, recording the last month's production prior to deepening and the production following deepening would have been advisable in order to show in the history an increase of water or oil after deepening.

From the history one would imagine that the well made water, and it was redrilled, starting June 27, 1915. The 8½-inch casing was finally recemented at 1,722 feet. The reader will note that although some 10-inch casing was left in the hole, it was filled to 1,510 feet with cement to prevent the 10-inch casing serving as a conductor for the water to work down into the oil sands.

The history of the well could be improved by giving more data on oil and water production, thus, after plugging to 1,815 feet in September–December, 1916, the record should show the resulting production of oil and water. The cause for doing each job should be recorded when known.

CROSS SECTIONS.

Cross sections are fundamentally necessary for studying the underground conditions in wells. The formations are determined by the findings of wells being drilled, and the cross sections are used to correlate these formations from well to well. Even in a region of simple geologic structure and stratigraphy, cross sections are necessary to bring out the local folds. Irregularities of well depths and casing depths can be studied by the use of cross sections. The discovery of an oil zone cased off in the wells or a deeper oil sand may be pointed out by comparing different graphic well logs on a cross section.

Cross sections in fact form the basis of the work of the engineer in studying underground losses and methods of prevention. Their many uses will be brought out in the pages following.

SELECTION OF THE LINES OF CROSS SECTIONS.

The selection of the well logs to plot on cross sections needs careful attention. This can best be accomplished by drawing a series of lines with a straight edge through different wells on a map showing the well locations. The lines of cross sections should be so selected that enough graphic well logs occur on more than one cross section to permit correlating from one cross section to another. All unnecessary duplication of graphic logs, however, should be avoided, as this adds to the expense.

To aid in correlating, it is particularly advantageous to have one or both end wells of each cross section overlap; that is, the log of the end well should be plotted on some other cross section. It is often advisable to extend a cross section so as to include neighboring line wells.

The selection of the line of cross sections is often arbitrary, for when the wells are spaced uniformly it is a case of selecting a series of parallel lines, often at right angles to another series, with perhaps a few diagonals. It is desirable to have some cross sections plotted parallel and others at right angles to the major axes of the structure.

PROJECTION OF A WELL TO A CROSS SECTION.

The graphic log of every well on the property should be plotted on some cross section. If none of the lines of cross section passes through a well location, this well should be projected to a near line because one well may give the key to a difficult problem. If the angle between the line of strike and the cross-section line is not very acute, it is frequently convenient to project a well along the strike into the cross section. Though wells are often projected into a cross section at right angles, there is no sound geologic basis for so doing, because with steeply dipping beds a right-angle projection makes no allowance for the dip. A right-angle projection should occur only when the beds are horizontal or nearly so, or when the strike is at right angles to the line of cross section. Of course, if the marker is definitely known in a well, it may be projected at right angles into the cross section and plotted in such a way (by elevation or depression) that the line drawn between the marker of the two wells on either side passes through the marker of the projected well.

PLOTING OF CROSS SECTIONS.

From the well logs and the location and elevation of the wells, the engineer can prepare the cross sections. The general method of plotting graphic well logs, which are used in cross sections, has been discussed on pages 26 to 34. To be of the greatest value, cross

sections should emphasize the important points, as stated on page 26, the writer does not advocate recording on the graphic well log the figures showing the depth of the top and bottom of each formation, for these figures tend to obscure the features used in correlating.

COST OF PLOTTING.

Records kept by the California State Mining Bureau¹² show that the cost of preparing graphic logs on cross sections with a scale of 100 feet to the inch averaged \$0.0384 per inch. The draftsmen were paid \$75 per month. They plotted on an average 4.1 graphic well logs per day of 7 hours. The average length of graphic logs was 20 inches. This cost includes the notes needed on production data and the printing of the title.

SELECTION OF SCALE.

In plotting graphic well logs (see p. 30) a scale of 100 feet to the inch will show a 2 or 3 foot change in formation, which is as accurate as most well logs. The horizontal scale for indicating the spacing of wells should, as a rule, be the same as the vertical. Only in special cases should different horizontal and vertical scales be

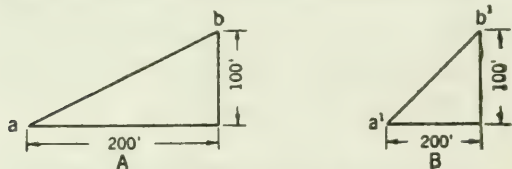


FIGURE 7.—Sketch showing how horizontal scale smaller than vertical scale exaggerates the dip of a bed. $a'b'$ is steeper than ab .

used, and even then the difference in scale should always be borne in mind; because a horizontal scale smaller than the vertical scale gives an apparently greater dip. In A, of figure 7, the horizontal and vertical scales are equal, which gives a true picture of the slope of ab ; in B, the horizontal scale is one-half that of the vertical, which gives an exaggerated picture of the dip of $a'b'$. If the vertical scale were smaller than the horizontal the slope of the line would be flattened.

PLOTTING.

There are two general methods of preparing cross sections—one where the graphic well logs are plotted on a single piece of tracing cloth and the other where the graphic well logs plotted on strips are arranged together for a cross section. A discussion is given of these two general methods.

After selection of a line of cross section for plotting and a scale chosen, a dashed line representing sea level or datum is drawn on a piece of tracing cloth of sufficient size. Starting at one end from a

¹² Personal communication, R. E. Collom, petroleum technologist, U. S. Bureau of Mines.

given well location, the various well locations are scaled off on the datum line. (See Pl. III.)

This scalar form (see fig. 5, p. 30) is placed under the tracing cloth, with the center of the scale spotted at a certain well location. The guide lines of the scale should be at right angles to the datum line. The scale is moved up or down until it bears proper reference to the datum. For instance, if a well has an elevation of 850 feet above sea level, the 850-foot mark of the form should coincide with the sea-level line. After blocking the vertical lines of the log on the tracing cloth to the scaled depth of the well, the formational changes can be drawn in with a ruling pen at the scaled depths. The depth is easily estimated to the nearest foot and the plotting of the graphic log of each well proceeds as discussed on pages 30 to 32.

Some companies plot each cross section on a separate piece of tracing cloth as described, but this wastes cloth and the plotted log is limited to the one cross section. A more economical method is to plot a set of graphic well logs on strips of tracing cloth 3 or 4 inches wide. The form of figure 5 is used for this work. One graphic plot then serves for any number of cross sections. A cross section on blue-print paper can be made from these graphic well logs as follows: Place a piece of blue-print paper of estimated size in the blue-print frame. Then stretch a string over the paper to serve as a sea level or datum line. The string should be firmly tied at either end. If the frame used turns over so that the logs are placed face down on the glass, a black line drawn across the glass will serve as a sea level or datum line. The graphic log strips can then be pinned down at right angles to the string at proper scaled distances apart and with proper reference of their elevation. Negatives to give blue-line prints with a white background can be made in the same manner.

It is also possible to pin blue prints of these strips on a board along the datum line, at scaled distances, representing the well locations, but in doing this only a temporary cross section is made. For reference purposes and working purposes, it is better to make a separate blue line or black line print on a white background. As stated on page 32, prints on a white background are preferable.

The cross section should show (see Pl. III) the well number of each well, its elevation, production data, a key map indicating the location of the line of the cross section, and the title. The legend of the formations need not be put on all cross sections, as the symbols should be standardized and the same symbols used on all cross sections. The lines of correlation can be drawn in as soon as they are established.

A system of plotting cross sections is used in which the well casing is represented in perspective and the formations connected up between

different wells. This method is useful for men unaccustomed to reading drawings, as it permits a better visualization of the underground conditions. The method, however, sacrifices speed and requires a scale for the casing out of the proper proportion.

CORRELATION OF CROSS SECTIONS.

The correlation of cross sections is based upon recognition of identical strata in the logs of many wells. The surface beds often indicate the direction of the slope of the beds underground which will at the start indicate the direction of the correlating lines on the cross sections. Graphic well logs may be correlated by matching them as follows:

Place two or more logs side by side and slide them up and down until the formations match. Two parallel cross sections can be satisfactorily studied by superimposing one cross section, drawn on tracing cloth, over the other section. The relation of water shut-off, occurrence of water, etc., of the two sections are thus readily brought out.

The detection of the same oil sand or water sand in different wells may be indicated by the formation's content. In a territory where there are two producing wells it may be doubtful whether or not they are producing from the same sand. An analysis of the oil from each well may give a clue. The same is true of water sands, as chemical analyses will determine whether the waters from different wells are coming from the same sand. (See under "Chemical analyses of water," pp. 88 to 90.)

Formations samples are very useful in correlating well sections. Paleontology is of increasing importance in the detection of identical formations in different wells. Formation samples (see p. 25) are analyzed¹³ to show their chemical composition and often examined with a microscope.

AID OF SURFACE GEOLOGY.

In correlating the underground formations of an area, the surface structure often serves as a guide. It may be of real value in studying wells spaced far apart, as the general surface dip may indicate the attitude of the beds underground. However, unconformities and other irregularities may cause the underground and surface formations to have different dips. The correlation of surface and underground geology is discussed later, on pages 67 and 68.

MARKERS OR KEY BEDS.

In correlating or identifying strata in oil wells, easily recognized formations of uniform thickness and occurrence are termed "markers" or "key beds." An ideal marker is a formation which persists

¹³ See Udden, J. A., Some deep borings in Illinois: Bull. 24, State Geol. Survey, Univ. Illinois, 1914, pp. 16-22.

from well to well, is of uniform thickness, and can be readily recognized when the drill strikes it, either by color, hardness, or toughness. A marker should be located preferably near and above the oil zone, but not in it. Often a marker is not only an easily identified stratum but may be a certain sequence of strata, which as individual members would be inconspicuous. Markers are identified from samples of the formations, also from certain drilling characteristics which make a formation easily recognized. Paleontology is of assistance, and micropaleontology is becoming very important in the oil fields of northern Texas.

The reader is referred to Udden's report ¹⁴ on "Some deep borings in Illinois," his handbook ¹⁵ on "Aids to identification of geological formations," and Aurin's paper ¹⁶ on "Correlation of the oil sands in Oklahoma," for information on correlation.

From the prints of the plotted cross sections, the engineer should try to trace the marker from one well to another. Having several markers is preferable because if one is lacking in a well another may be recognized. The correlation should be carefully made, for it is the basis of cross sections and structure maps used in studying water and other problems.

Thick beds of sand, shale, or other rocks are most easily identified. Either the top or the bottom of a bed should be used, depending upon which is the more persistent. Oil, gas, and water sands are good markers, also beds containing sea shells, limestones, and coal beds are dependable in some areas. As soon as a few logs are studied a marker can be chosen which should be identified in different wells. For emphasis, the marker can be connected from well to well on the cross section by a red line, or other distinctive color.

In the Caddo field ¹⁷ of Louisiana, the Nacatoch sand is an excellent marker, for it is hard and of uniform thickness throughout the greater part of the Sabine uplift in northern Louisiana, and drillers experienced in this area recognize it easily.

In certain areas of Oklahoma, persistent limestones of uniform thickness occur and when near the oil horizons are good markers. In the Gulf Coast they are not so dependable. In southern Oklahoma in the general vicinity of Duncan, Lawton, and Loco, the base of the Permian Red Beds is likely to be of material assistance in determining the proper casing depths of that area.¹⁸

¹⁴ Udden, J. A., Some deep borings in Illinois, Bull. 24, State Geol. Survey, Univ. Illinois, 1914, p. 141.

¹⁵ Udden, J. A., Aids to identification of geological formations, Handbook Series, No. 1, Univ. Texas, Bureau of Economic Geology and Technology, p. 69.

¹⁶ Aurin, Fritz, Correlation of the oil sands of Oklahoma: Oklahoma Geol. Survey, Circular No. 7, October, 1917. 16 pp.

¹⁷ See Matson, G. C., The Caddo oil and gas field, Louisiana and Texas: Bull. 619, U. S. Geol. Survey, 1916, p. 30.

¹⁸ See Aurin, Fritz, The geology of the Red Beds of Oklahoma: Bull. 30, Oklahoma Geol. Survey, 1917, 66 pp.

In the East Side field of Coalinga, Calif., a red clay of varying thickness, termed "red rock," is used as a marker by many on account of its color. Although this bed has a distinctive color it is not as regular as the "Big Blue" shale, a series about 200 feet thick, which has the red rock as one of its members, the red rock occurring at various depths. The contact of the top and base of this formation with the sands is far more constant than that of the popularly used red rock.

An example of a correlated section is shown in Plate III. The reader can see at a glance the following contacts which can be traced from one well to another: Top of the Big Blue shale; base of the Big Blue shale (which is also the top of the tar sand); the top of the Sauer Dough sand (the first producing sand); and the top of the Brown shale.

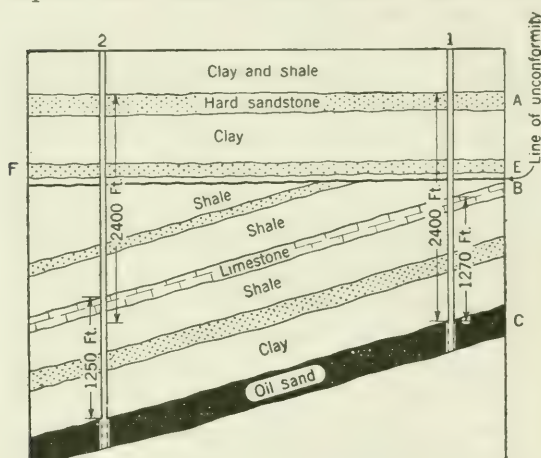


FIGURE 8.—Sketch to show advisability of selecting markers near oil horizon. In drilling well 2 with 1 as a guide, the operator would have trouble in locating oil sand C if he used A as a marker, but with B as a marker he could predict its location to within a few feet.

CORRELATION AND UNCONFORMITIES.

Markers should be selected as near the oil horizon as possible, for

with a shorter distance between the marker and the productive zone there is less liability for the thickening and thinning of formations from one well to another. Also, there may be a slight unconformity between the top beds and the oil zone, then the oil sand would not occur at the same distance below the top marker.

Figure 8 is a hypothetical sketch to show how an unconformity between the upper and lower beds might mislead the operator in finding the location of oil horizons in drilling wells. If well 2 was drilling after well 1 had been brought in, and the operator used the hard sand A as a marker, he would expect to encounter the oil sand C, in well 2, at 2,400 feet below the top of sand A. Actually, the oil sand would be much deeper. Had he used the top of marker B

700'

800'

900'

10'-963'

Landed

1000'

1100'

1200'

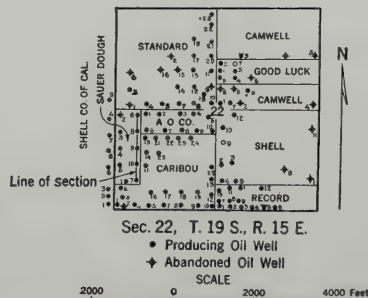
84'-1308'

SEA LEVEL

Comple

Init. prod.

Gravity



(For legend of symbols see fig. 4, p. 27.)

in well 2 to predict the depth of the oil sand he would expect to find oil at 1,270 feet below B; the actual depth would be 1,250 feet.

No suggestions as to the true underground conditions would be found until after encountering limestone B. In well 2, the top of sand A in both wells would parallel the flat surface dip, and the tops of the beds penetrated above E-F would indicate that the deeper beds were conformable to the surface, which would add to the puzzle for not finding oil in well 2, 2,400 feet below A.

DETECTION OF FAULTS IN CORRELATION.

Faults, of course, throw the beds out of their expected location, and producing sands may be raised or lowered by faulting. Such a disturbance naturally complicates well problems. A. A. Hammer and R. A. Cattell,¹⁹ petroleum engineers of the bureau, found in their study of underground conditions in the southeast extension of the Healdton oil field, Oklahoma, a fault which was a material factor in the production problems of that district.

Bates²⁰ discussed how an underground study was of practical use in northern Louisiana. A fault was located by a study of well logs which explained why certain wells were not productive, or, as stated by Bates, "Every well south of the fault was dry, as predicted."

The engineer should not be too hasty in concluding that the region is faulted if the horizontal and vertical scales used are not equal. The possibility of indicating an exaggerated dip by the use of unequal scales is brought out in figure 7 and the discussion on page 36.

APPARENT THICKENING OF STEEPLY TILTED BEDS.

In correlation, the various beds are assumed to be parallel until it has been demonstrated otherwise. Formations do vary in thickness, but where the dip of the beds becomes suddenly steep, the cross sections would erroneously indicate a thickening of the beds, because the drill cuts through the beds at an angle and has to travel a distance greater than their actual thickness. (See fig. 9.)

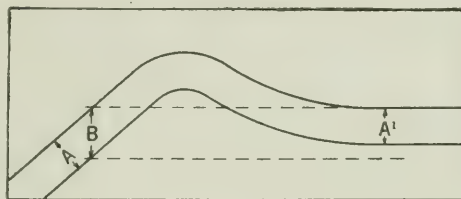


FIGURE 9.—Sketch showing how drill has to penetrate greater thickness of formation in steeply dipping beds. A equals A¹ but B is greater than A¹.

¹⁹ Hammer, A. A., and Cattell, R. A., Relation between operating methods and the occurrence of water in southeast extension of the Healdton oil field, Oklahoma. Unpublished report, U. S. Bureau of Mines, Muskogee, Okla.

²⁰ Bates, Mowry. A concrete example of the use of well logs: Am. Inst. Min. Eng., Sept., 1918, pp. 979-986.

This is noticeable in some fields of California and on the sides of certain salt domes in the Gulf Coast region, where the beds may dip steeply.

LENTICULARITY AND CORRELATION.

The very nature of the deposition of sediments under water, with resultant spits, bars, terraces, etc., means that lenticular beds of sand, shale, limestone, and other sedimentary rocks are common. Therefore, lensing formations are common in many oil and gas pools. In beds which are extremely lenticular the thickening and thinning of the bed formations give rise to some very puzzling problems. (See discussion on lenticular water sands, p. 148, and fig. 22.) A bed may pinch out entirely from one well to another.

Hammer and Cattell²¹ reported on the Healdton oil field, Oklahoma:

"The sands containing oil were so lenticular in character that it was practically impossible to contour the top of any producing sand. It was also found that the structure is very irregular, but that in general it is an anticline plunging almost due east. Consequently, in lieu of a contour map a number of cross sections have been drawn east and west and north and south through the area, not only setting forth the general features but delineating as far as possible the methods of oil-well operations and the resulting effect on the occurrence of water in wells."

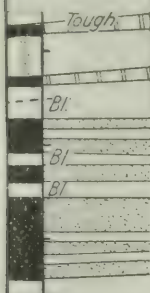
Special care and judgment should be used in correlating beds where the formations are lenticular. Often several correlations can be made from a given number of graphic well logs. This is brought out in Plate IV, where it is seen that different lines of correlation could be drawn and that some of them might even be more nearly correct than those assumed.

T. E. Swigart, petroleum engineer of the bureau, furnished the writer with "A concrete example of the correlation of lenticular sands," which is quoted herewith.

Through the courtesy of Mr. B. E. Parsons, of the General Petroleum Corporation, the writer was able to obtain the logs of a certain line of wells in the Belridge field in order to illustrate the correlation of lenticular sands in a closely drilled area. The accompanying diagram (Plate IV) shows the details of this work.

In attempting a correlation of this kind the engineer is guided by structural features, analysis of oils and water obtained from certain sands in adjacent wells, the location of oil, gas and water sands, and other characteristic formations, as well as by his personal acquaintance with the history of each well. No single feature is enough to assure one of the correctness of his work, but the final correlation is the result of gradual progress made, after resorting to every possible hint throughout the work. Frequent tests made on a drilling well lend more certainty to the problem but it is difficult to convince some companies of the justification of the extra work and expense.

²¹ Hammer, A. A., and Cattell, R. A., Relation between operating methods and the occurrence of water in southeast extension of the Healdton oil field, Oklahoma: Unpublished report, U. S. Bureau of Mines, Muskogee, Okla.



Depth 960'
Comp. 4-18-17
settled prod. 20

LENTICULAR



Upon examining the Belridge cross section, shown in Plate IV, it will be noticed that a "shell" was found in five wells from 12 to 20 feet above the highest tar sand. The fact that this horizon is parallel to the top of the first tar sand, which is logged in every well, is an additional indication of the structure to be expected below.

For the most part the sands will correlate readily by accepting the structure indicated by the upper tar sand and shell layers, but when a sand occurs in one well and a long streak of blue shale is logged at the same stratigraphic position in an adjacent well, the engineer must look for new facts to determine whether this sand has graded into shale, has pinched out, or whether the oil sand was not recorded through careless logging.

Indeed, if the logs could be depended upon, the problem even then would not be so difficult, but the knowledge that an area is underlain by lenticular formations, coupled with the uncertainty of accurate well logs, causes one to proceed with the utmost care. For instance, in well 18, Plate IV, the driller has logged oil sand from 765 feet to 810 feet, and from 855 feet to 940 feet, whereas in the wells on either side these sands are not shown as two thick beds, but as five distinct sands. Hence one is justified in believing that the driller of well 18 was probably wrong in logging a continuous sand. As this occurred twice in the same well, additional weight may be given the probability of careless logging.

The value of a water sand as a marker is shown in well 50, Plate IV. Sulphur water and oil are shown at 760 feet and 770 feet. In well 43 an attempt was made to shut off the water in this sand by cementing a string of casing at 780 feet, but the job was unsuccessful, so the 8½-inch casing was cemented at 816 feet, which shut off the water.

In well 36, after passing through this tar sand, which carried water, a string was cemented at 744 feet, presumably below that sand, but, as a matter of fact, the well was still wet when drilled into the next lower tar sand and another string was cemented at 785 feet. Such an observation then points toward the belief that the tar sand was divided by a wedge-shaped bed of shale and was thus encountered at two depths in well 36. Following this same sand the upper bed is soon to diminish in thickness until in well 22 it is not logged at all, but in well 18 a sand is logged at the same stratigraphic position. This sand is about 20 feet thick; whether it pinches out for possibly a hundred feet and then comes in again is not known. The indications are that it does.

In well 2 there is 16 feet of oil sand logged at 811 feet, followed by sandy shale. The fact that the combined thickness of this oil and sandy shale is practically equal to the thickness of the oil sand shown in the wells on either side indicates the difference of logging formations by different drillers. Probably the formations logged as sandy shale in well 2 would have been logged as a sand by the driller of well 11.

The upper zone or sand in this area contains a number of nonproductive tar sands, some of which carry water. Between these sands and the lower productive zone is a bed of shale of uniform thickness, in which occur lenticular tar sands. Below this shale the productive oil sands are found, lenticular in character and interbedded with blue shale. These sands occur for about 160 feet and are of uniform thickness. This affords an additional key to the correlation of the area. It makes little difference whether every detail of correlation is correct in this productive zone or not. The top of the productive zone and safe depth to drill without encountering bottom water are very important.

The key map in the lower right-hand corner of Plate IV shows the edge-water line passing through well 36. The shaded portion represents the area in which the edge water has advanced in sand "A." (See Pl. IV midway between wells 50 and 43.) This is shown in wells 50, 43, and 36, in which it was necessary to shut off the water below this horizon while in the remainder of the wells which are upslope, the water string is landed much higher stratigraphically.

Detailed information on territories even fully developed is usually lacking, and for that reason the work of the engineer is made difficult. Obviously each company should employ an engineer whose duty it is to protect the property and extend every effort to prolong the life of the wells. He should be present at the wells when the drill is about to penetrate a "marker" or sand. He should learn to identify the various formations, as the field work is of great aid in the office study of various problems. Naturally the field work involves a close observation of all details of development of the territory and thus provides first-hand information as a basis of solving future problems with greater ease and certainty.

GRAPHIC LOGS PLOTTED TO STRATIGRAPHIC DATUM.

In certain cases the plotting of well logs to a common stratigraphic datum is an advantage. After a marker or key bed has been definitely determined the wells may be plotted on a single sheet, each well being plotted from the marker or from a certain distance above or below the marker, to the bottom of the hole. Then, if the formations are regular, or of uniform thickness, the line connecting the top of each bed should be horizontal; that is, the lines of correlation are horizontal.

The purpose of this form of graphic presentation is to eliminate the confusion arising from the structural folding of the beds. This is done by an adjustment to a horizontal plane, which makes the beds appear flat. One must be careful in using it, particularly where beds dip thickly or steeply in one part of the area. By this plot, all wells can be shown whether or not they are in a line of cross-section.

In figure 10—which shows graphic logs of wells of the Shell Co. of California, on section 14, T. 19 S., R. 15 E., Coalinga—the wells are plotted in numerical order from left to right. Starting with the marker as the zero point, the distances below the marker are shown by 100-foot parallel lines. In certain areas it might be advisable to plot a small group of wells rather than all the wells on a section of land; that is, plot all wells in a certain quarter section. In plotting, the wells are placed sufficiently far apart so that the data are not confusing.

This sort of diagram shows at a glance the relative cementing depths, perforations, well depths, etc., of the different wells. Given fairly uniform conditions, one would expect all water shut-offs to be a certain distance below the marker, hence, along a horizontal line. From well 20, which makes no water, evidently the engineer could

expect that the water strings of various wells might be landed with safety about 600 feet below the marker.

The line drawn from one cementing depth to the other does not extend horizontally along the —600-foot line, but zigzags from well to well; in wells 10, 13, 14, and 15, the water string has been cemented too low, thus shutting off an oil sand.

Again, wells 13, 14, and 16 have been plugged to shut off bottom water. Under uniform conditions, any bottom-water sand would be expected to occur at about the same distance below the marker in all

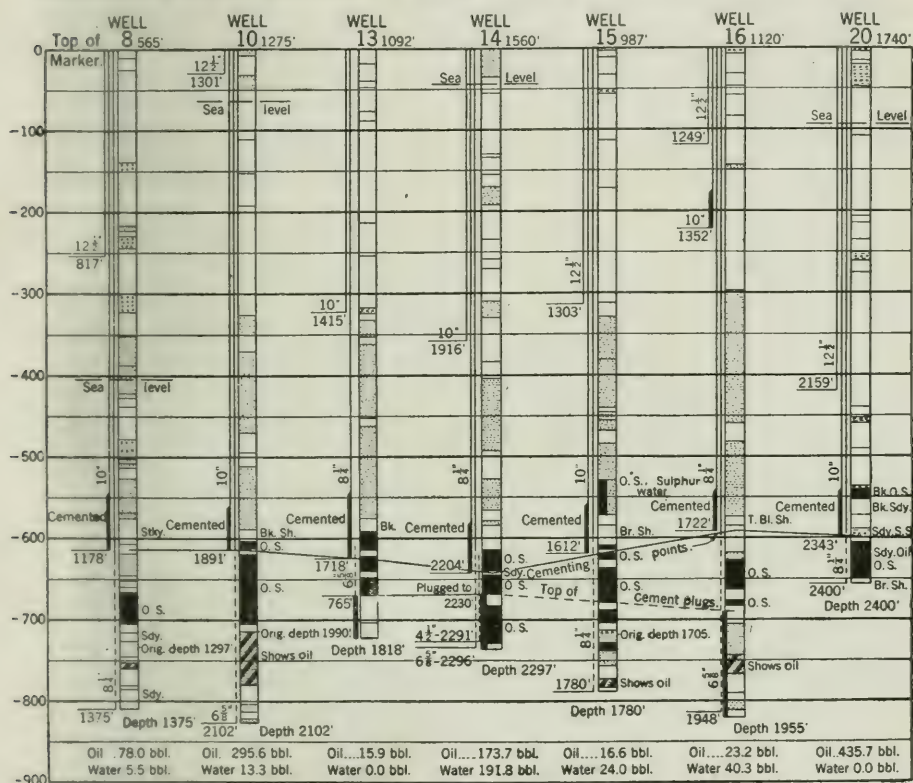


FIG. 10.—Well logs plotted to common stratigraphic datum to show the comparative well depths, water shut-offs, perforations, etc., of different wells. For legend of formation symbols, see fig. 4.

the wells. Therefore, in plugging to shut off bottom water, the tops of the plugs should, in such a section, be more or less along the same horizontal line.

Another use of this diagram is to compare the well depths. In figure 10, well 10 has been drilled 827 feet below the top of the marker, and well 20, only 660 feet. This marked difference is seen at the first glance. In the study of underground problems, such a section has

many practical uses which will be self-evident after reading the discussion of the various problems outlined on page 5.

UNDERGROUND-STRUCTURE CONTOUR MAP.

DESCRIPTION OF MAP.

The underground-structure contour map—for examples, see figure 20 (p. 84) and Plate XIX (p. 150)—has been used extensively in oil-field operations to depict the attitude of an unexposed bed over a considerable area. The folding or faulting of a bed is shown on such a map by means of contour lines. A *contour line* is the projection upon the plane of the paper of the intersection of a horizontal plane with the top or base of a bed. Most often the surface selected for platting is the top of a producing oil sand. A contour line, therefore, connects on the surface of a bed all points having a certain altitude.

A *contour map* is made up of a series of contour lines spaced at uniform intervals of elevation to show the configuration of a contoured bed. The *contour interval* represents the regular intervals of elevations as denoted by the contour lines. In explanation, a surface contour line may be represented as the intersection of a horizontal plane cutting the side of a hill 500 feet above sea level. The contact of this plane and the hillside would make an irregular line, all points of which are 500 feet above sea level. A contour line would be a graphic representation of this line of the map.

With uniformly dipping beds the distance between contours on a map would be practically equal, while with an increase in dip the contour lines would be closer together and with a decrease in dip the space between the contour lines would widen. With 25-foot intervals and a succession of contour lines, such as 450, 475, 500, 525, etc., the 500-foot contour would be a line all points of which are 500 feet either above or below some reference plane. This reference plane is arbitrarily selected so that the contour lines may represent either plus or minus elevations. The datum most commonly used is sea level.

PREPARATION OF MAP.

Before starting work on a structure contour map the datum plane should be chosen. Sea level has been adopted in many areas, but it has been found desirable in certain districts to select a datum plane either above or below sea level in order to avoid plus and minus contours on the same map.

Constant work on a set of either minus or plus contours is preferable to making some maps with minus and others with plus contours, as familiarity and practice with one system lends to speed.

In preparing a contour map, the engineer determines the reference plane, the contour interval, and the key bed to be contoured. The reference plane is usually sea level. The contour interval depends on the nature of the folding or faulting of the beds, the data available, the scale used, and the purpose for which the map is to be used. The bed to be contoured is usually an oil sand, but in any event it should be a recognizable key bed near the oil zone. A marker near the oil sand is preferable as with less formation between the oil sand and the marker, there is less opportunity for thickening or thinning of formations.

By a study of well logs, or preferably cross sections, the distance between the bed to be contoured and the datum plane is computed for each well, and written down beside the well's location on the map. Suppose that in two wells one shows the marker 400 feet and the other 500 feet below the datum plane. Then if a 25-foot contour interval is used, a light line is drawn between the two well locations and subdivided into four equal parts. These points then represent contour points 400, 425, 450, 475, and 500 feet below the datum plane. Similar lines are drawn between adjoining wells and subdivided, after which the lines of equal elevation or contour lines are drawn.

Where the distances between the marker and the datum plane in two wells is not an exact multiple of 25 (the contour interval), then the line connecting the two wells should be proportionally divided at the 25-foot contour points. For example, the marker in the first well may be 410 feet below the datum plane, and that of the second well, 520 feet below. The vertical difference between the marker at the two wells is 110 feet. The 500-foot contour point would then lie measuring from the second well $\frac{20}{110}$ of the horizontal distance between the two wells, the 475-foot contour would be $\frac{45}{110}$ of the distance, etc. With experience, these subdivisions can be rapidly estimated by eye. After a reasonable number of contour points has been established, the contour lines may be drawn. The above method of proportion makes the method entirely mechanical. As a matter of fact, conditions can not always be represented correctly by taking proportional parts. The engineer must use his best judgment in drawing in the final contour lines.

FACTORS DETERMINING ACCURACY OF MAP.

The accuracy of an underground-structure contour map depends on the number and distribution of the wells over a given area, on how accurately the wells have been logged, and their location and elevation determined. The selection of a well-defined marker, or key bed, is essential, as its uniform recognition determines the accuracy of the work. Where the area is fairly well drilled up a very accurate contour map may be made which will show even minor

folds, but where little drilling has been done the contours are in places more or less conjectural unless there is surface evidence that can be used.

As oil men are most interested in the underground conditions, the data to be used are primarily the well logs, although in sparsely drilled territory a combination of well logs and surface exposures is often used to advantage if the oil-bearing beds are conformable to the surface beds. (See p. 68.)

USES OF MAP.

The uses and advantages of underground-structure contour maps are discussed more fully in the text under the various subjects mentioned on page 46. The chief value of such maps is to show broad structural relations over a large area in a way not usually shown by even the most careful study of geologic cross sections of wells. Cross sections are limited to one vertical plane through a few wells. In regions with rocks of gentle folds and faults of small throw the geologic cross section does not show small dips as well as the contour map, but such sections are very useful in the more steeply tilted beds of California, Wyoming, and the Gulf coast.

In some fields where definite markers are easily recognized and where the producing oil zone is always encountered a uniform distance below the marker, cross sections for correlating the various beds are not always necessary in starting a structural map. Certainly in some parts of Pennsylvania, Kentucky, and West Virginia the driller can tell the depth to the oil sand after drilling to his marker. Where a marker is so evident, structural maps may be prepared without cross-sectional correlation. In most fields, particularly in new fields, cross sections are needed to ascertain whether the beds are regular, and are especially useful in mapping areas where the beds are irregularly folded or faulted, steeply tilted, or lenticular.

An underground contour map can often be used to show the following:

1. The location of the wells relative to the folds in the formation. (See fig. 20, on p. 84, which shows the domes and synclines of a portion of the Cushing oil field, Oklahoma, and Plate XIX, at p. 150, which shows a large monocline and plunging anticline of the East Side field, Coalinga, Calif.)

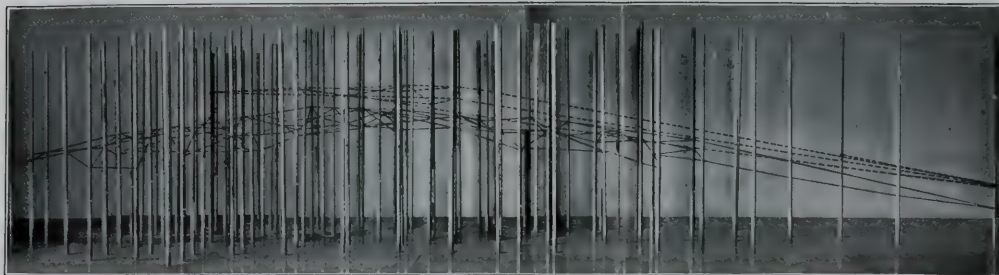
2. The most productive, as well as the least productive types of structure in a drilled territory. This can be accomplished by noting on the contour map the ultimate production per acre of different wells or the initial production of each well. (See fig. 39, on p. 180.)

3. The most favorable undrilled tracts for the accumulation of oil and gas, when the underground contour map is used in conjunc-

BUREAU OF MINES



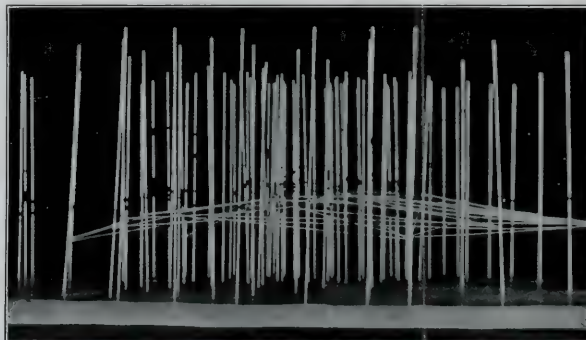
Each peg represents an



A. PEG MODEL OF COYOTE HILLS OIL FIELD, CALIFORNIA.

Each peg represents an oil well. The dome-like shape of the oil sands is shown by the two sets of strings connecting the two oil-bearing sands as found in the different wells. Strings may be used to connect well depths, etc., thus bringing out any irregularities.

(Courtesy of R. P. McLaughlin.)



B. PEG MODEL OF UNION OIL CO., SANTA MARIA, CALIF.

(Courtesy of W. W. Oreutt, Los Angeles, Calif.)

tion with the surface contour map, in an area where the beds are approximately parallel, which thus gives,

4. A trustworthy method of selecting future well locations based on the relationship between the structure and the actual production records of similar structures in the same area. (See following discussion, also the discussion on pp. 176 to 178, relative to the Boston pool, Oklahoma.)

5. The direction and amount of dips in all parts of the area covered by the structure map. The direction and amount of a dip of any part of a formation can be determined readily by computation. This method is limited only by the extent of the structure map and even then the structure contours will serve to predict the extension of the structure.

6. A means of calculating the approximate position of any bed, such as an oil sand, on any part of the area covered by the contour map, provided the surface elevation and distance between the marker and oil sand are known. (See discussion following.)

As regards the selection of well locations, the engineer may find that the oil production extends farther down the slope on the longer axes of the folds or, where a reverse dip occurs in a region with a general monoclinal plunge, that the most productive part is on the side of the normal dip. Therefore, he has a guide in determining the future well locations on similar structures in the same general area. Even the relation between the occurrence of oil and water may serve as a guide for water conditions in similar structures near by. In all of this work considerable discretion must be exercised owing to the differences in the occurrence of oil, gas, and water in the same field.

One of the most important uses of the structure contour map is in determining the approximate position of other underground beds in relation to the marker. For example, suppose that a limestone bed is used as a marker in compiling such a map, and the logs of drilled wells show that the top of the oil zone is 500 feet below this limestone. At a proposed well location which is on a contour line 400 feet below sea level and whose surface elevation is 1,035 feet above sea level, the drill should encounter the top of the oil zone at 500 plus 400 plus 1,035, or 1,935 feet from the surface. Thus, on any part of the area covered by the contour map it will be possible to predict the depth at which the oil sand will be found, provided the surface elevation is known at that point.

CONVERGENCE MAP.

Occasionally the upper or surface beds in some oil fields are not conformable or not parallel to those underground. Where the differ-

ence is large, a contour map of the surface beds does not properly indicate the attitude of the underground beds, nor can it be used alone in figuring the exact depth at which the oil sands may be found.

By using a convergence map (see fig. 11),²² which shows the rate of convergence, or divergence, of the different beds, in combination with a surface structure contour map, the engineer can often predict more accurately the depth of the oil and gas zones. In fact, a contour map of the oil sands may be made from these two maps.

DATA NEEDED FOR A CONVERGENCE MAP.

There is great danger in making a convergence map with too few points. The data needed for the preparation of a trustworthy convergence map are:

1. Accurate records of wells scattered over the area to be covered by the convergence map.
2. Accurate well elevations and locations.
3. A surface contour map of a key bed of the area.

In fact, practically the same material is needed for the preparation of a convergence map as for an underground-structure contour map. Except in special instances, the time spent in preparing a convergence map can be better used in the preparation of a contour map of the oil sand.

PREPARATION OF A CONVERGENCE MAP.

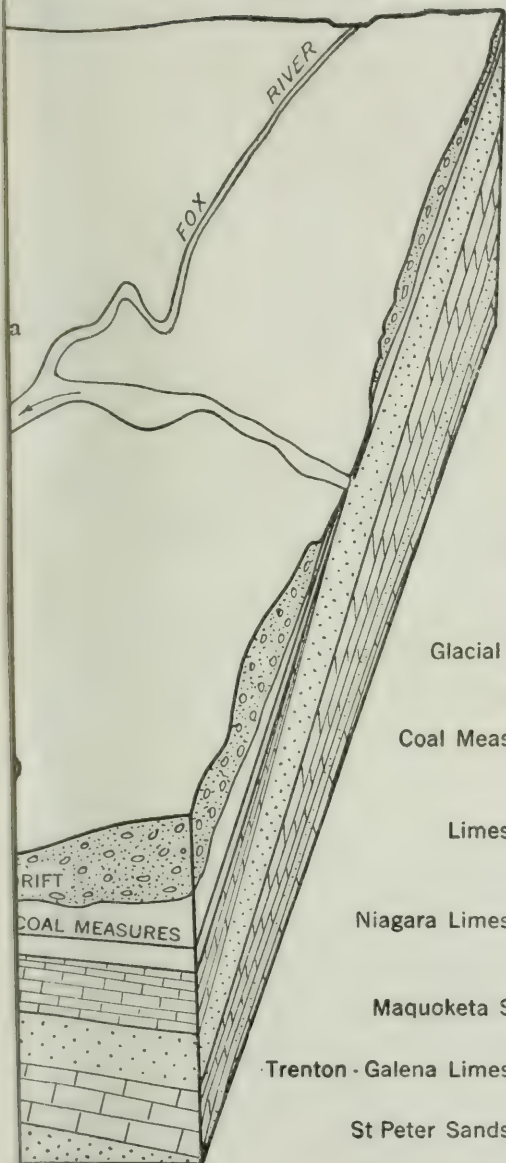
The method of preparing a convergence map is only briefly outlined here, as the reader can, if necessary, find detailed instructions in the literature.²³ First plot the well locations on the contour map of the surface key bed. On this map show each well number and its elevation. For each well compute the vertical distance between the key bed and the top of the well.

By the combined use of this figure and the depth of the oil sand, as found in the well, it is possible to compute the vertical distance between the surface key bed and the oil sand. The distance for each well should be recorded near the respective well locations upon a convergence map made on transparent tracing paper or cloth. This map should have the same scale as the surface contour map and should show the well locations and their number.

In many places the distances between the oil sand and the key bed increase or decrease in a certain direction. This variation in thickness is indicated by means of "isochor" (lines of equal inter-

²² After M. J. Munn, *Sewickley Folio* (Folio 176), field ed.: U. S. Geol. Survey, 1911, p. 56. A convergence map is usually prepared on tracing paper or tracing cloth, and is made the same size as the structure contour map.

²³ See Griswold, W. T., and Munn, M. J., *Geology of oil and gas fields in Steubenville, Burgettstown, and Claysville Quadrangles, Ohio, West Virginia and Pennsylvania*: Bull. 218, U. S. Geological Survey, pp. 23-25; also, Johnson, R. H., and Huntley, L. G., *Principles of oil and gas production*: First edition, 1916, pp. 207-209.



LEGEND

PLEISTOCENE

Glacial Drift 

PENNSYLVANIAN

Coal Measures  La Salle L's't.
Coal No. 2

DEVONIAN

Limestone 

SILURIAN

Niagara Limestone 

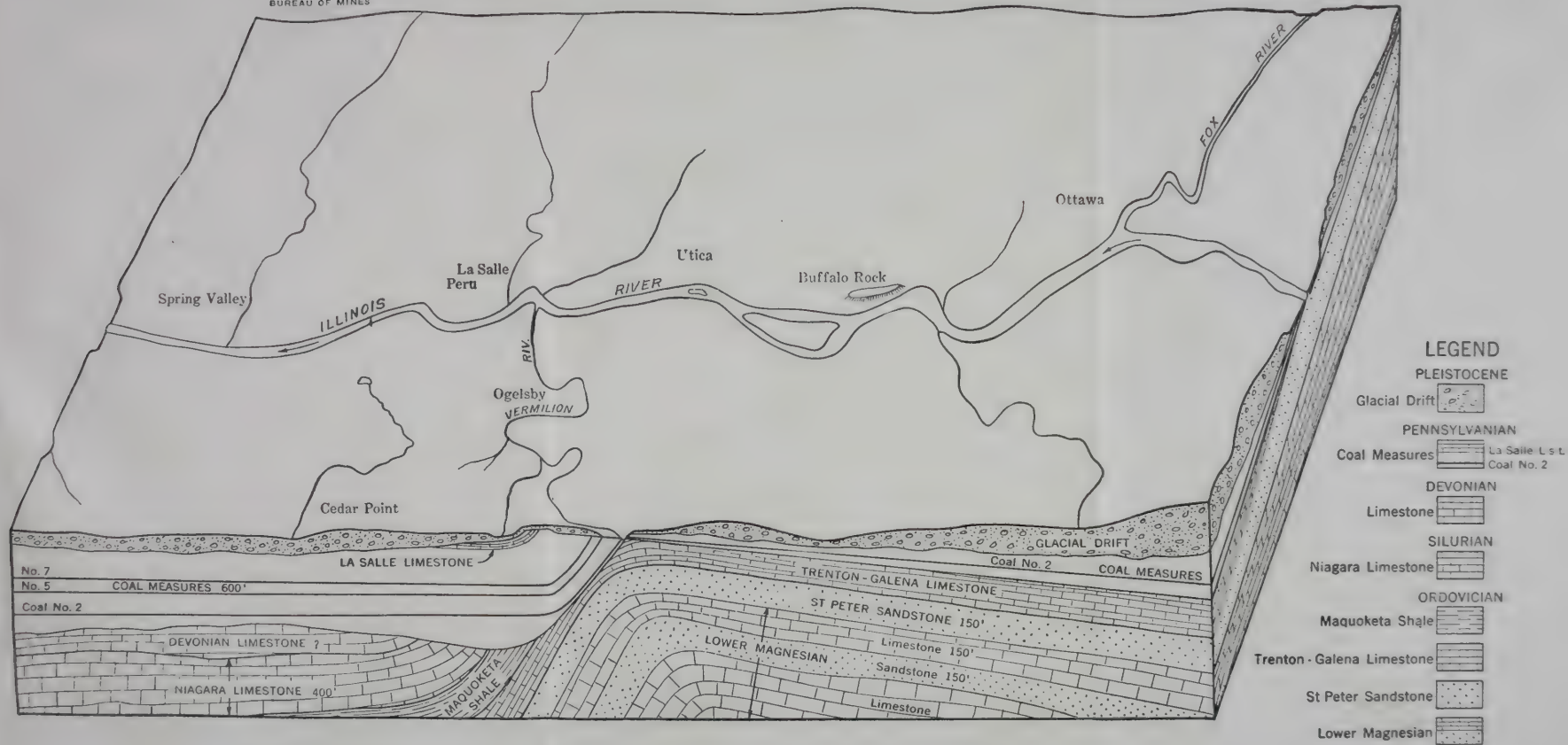
ORDOVICIAN

Maquoketa Shale 

Trenton - Galena Limestone 

St Peter Sandstone 

Lower Magnesian 



STEREOGRAM OF LA SALLE, ILL., AND VICINITY, SHOWING THE GENERAL GEOLOGIC STRUCTURE AND STRATIGRAPHY.

(Courtesy of F. W. De Wolf, director, Illinois State Geological Survey.)

val. "Isochor" lines are drawn in somewhat the same way as contour lines. A light line is drawn from one well to another well and this is proportionally divided at definite intervals according to the

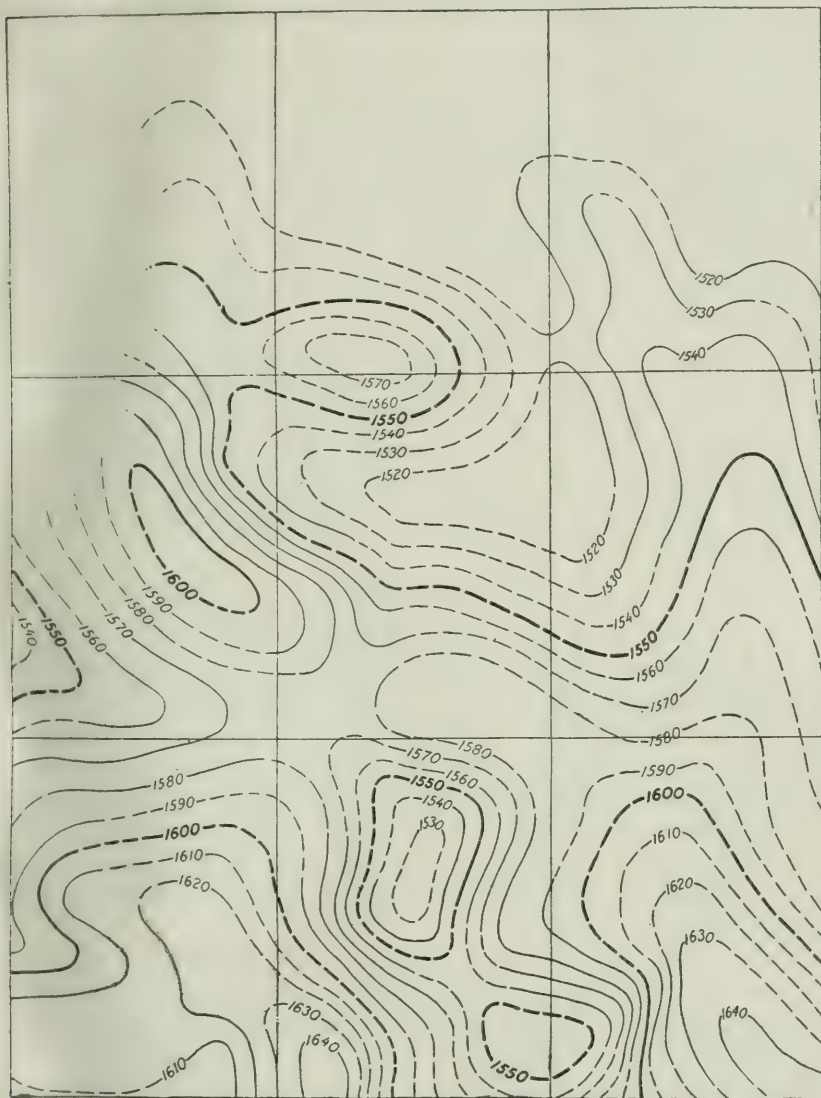


FIGURE 11.—Convergence map showing by lines of equal distance (isochor lines) the vertical distance between the Ames limestone member and the hundred-foot sand in the Sewickley Quadrangle. The lines are drawn to pass through points on the Ames limestones having an equal distance above the top of the hundred-foot sand. In areas left blank the Ames limestone has been removed by erosion.

amount of convergence found between the two wells. The interval used is usually a multiple of 5 or 10. The isochore lines are formed by connecting, for each given interval, or distance between key bed

and oil sand, all the points representing that distance. As in drawing contour lines, good judgment is necessary.

With a given well elevation, a convergence map, and a contour map of the key bed, the depth of the oil sand at any point on the maps can be predicted.

USE OF CONVERGENCE MAP TO PREPARE A CONTOUR MAP OF THE OIL SAND.

The convergence map, prepared on transparent paper, can be superimposed on the contour map of the key bed. From each intersection of an "isochore" line and a key-bed contour line one point can be determined giving an elevation on the oil sand. For example, if the contour has an elevation of 1,000 feet above sea level and the isochore shows a distance of 2,200 feet between the key bed and oil sand, then the elevation of the oil sand at that point is 1,200 feet below sea level. From such points of elevation a structure contour map may be made of the oil sand as described on pages 46 to 49.

As previously stated, practically the same data is needed for making a good convergence map as for making an underground-structure contour map, and an engineer beginning the study of an underground problem can use his time to better advantage in working up a contour map of the oil sand.

PEG MODELS.

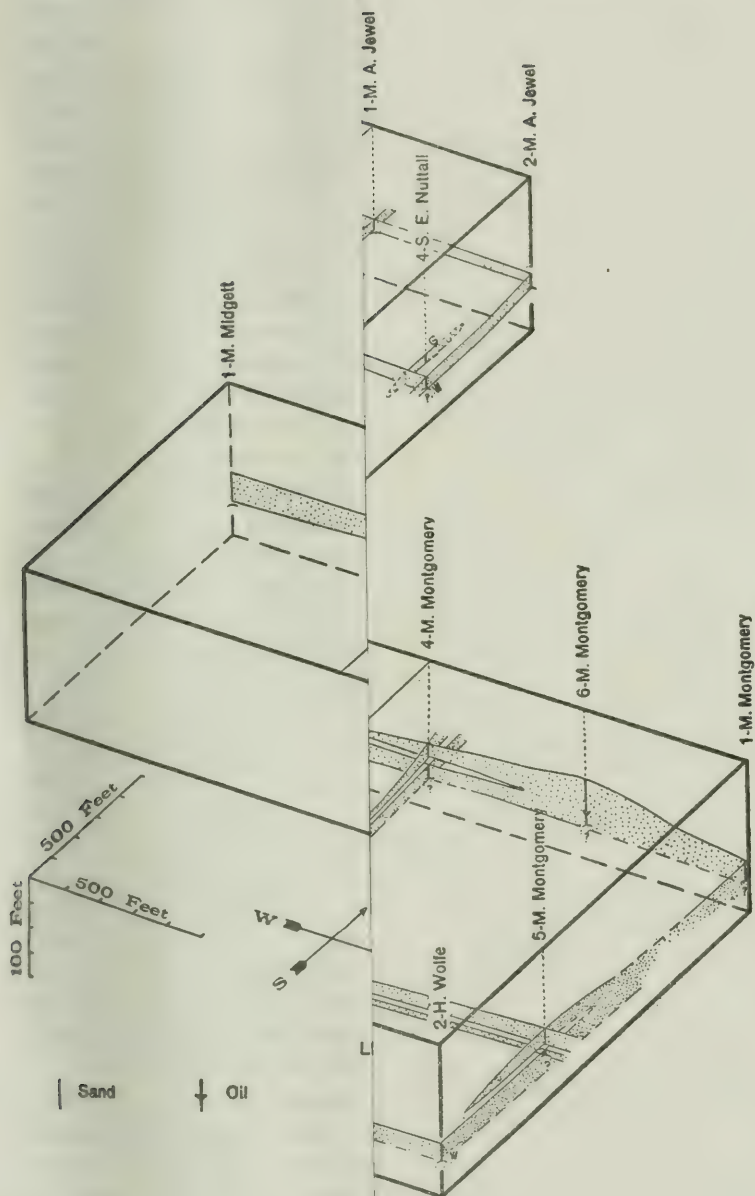
USE OF PEG MODELS.

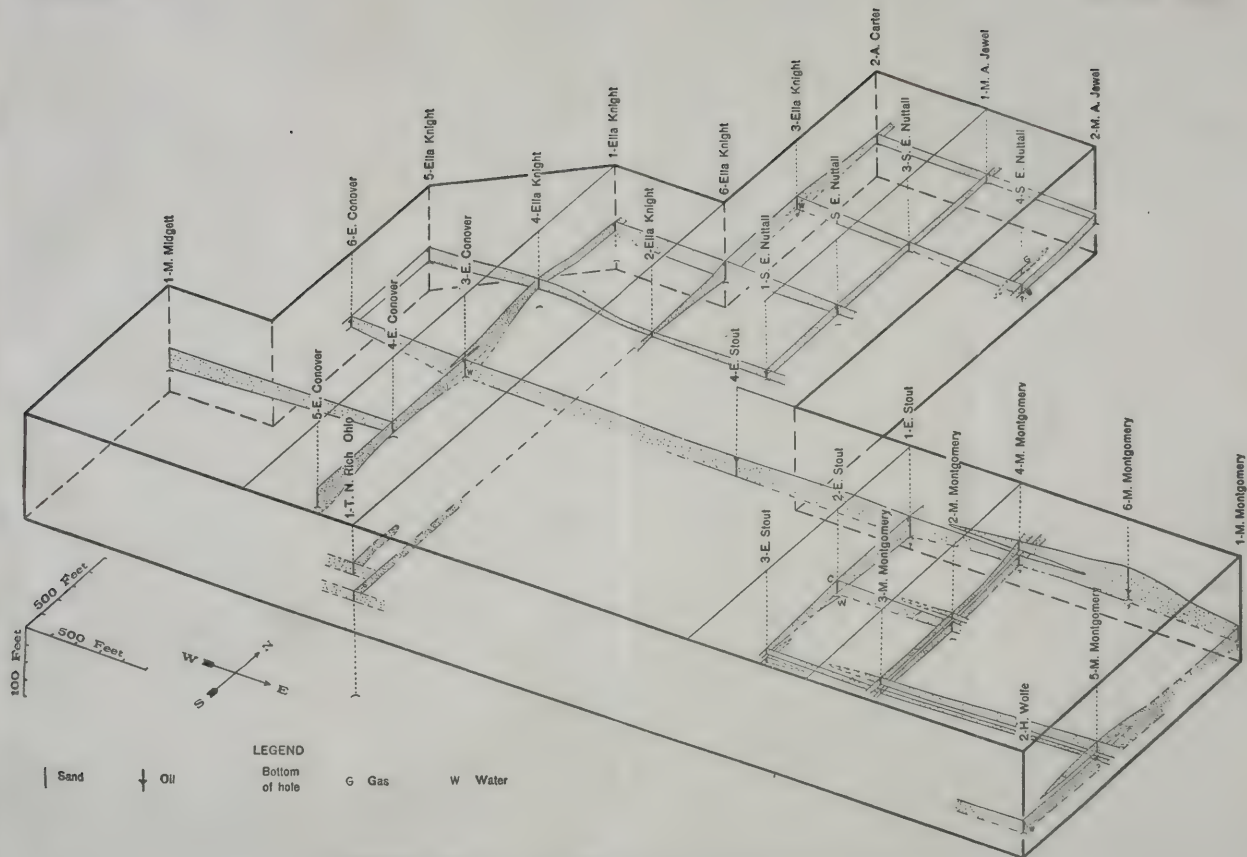
A satisfactory method for showing structural conditions underground, as brought out by drilled wells, is by the use of peg models. Models are particularly useful where the structure is pronounced and the sands irregular. They have the special advantage of three dimensions and bring out clearly the main features, which in cross sections often are obscured by details. The method has been found especially useful to the nontechnical man, who grasps readily the essentials from a model, whereas cross sections and contour maps are apt to be confusing.

Peg models are also used for correlation, in the studies of accumulation, for determining the proper points to shut off water, for the location of water, gas, and oil sands, perforations, proper casing depths, etc. Any marked irregularities of well depths, water shut-offs, etc., are brought out very well by peg models. Many companies in California and the Gulf Coast have prepared models and the California State Mining Bureau has peg models covering most of the California oil fields.

PREPARATION OF PEG MODELS.

A simple, cheap type of peg model is shown in Plate V, A. Pine board about an inch thick is used for the base. The baseboards are usually made according to scale in subdivisions representing





STEREOGRAM SHOWING CHARACTERISTICS OF OIL SAND IN BIRDS QUADRANGLE.

(After Illinois State Geological Survey.)

quarter sections or other tracts. These subdivisions or tracts can be joined together later for making a model extending over a large area. The baseboard should be of dry material and counterbraced against warping. The well locations are scaled off on the baseboard, or, as practiced by the California State Mining Bureau, a map showing well locations is pasted over the baseboard. The scale of such models is usually 100 feet to the inch, although in certain regions it may be necessary to use a scale of 200 feet to the inch. The horizontal and vertical scale should be the same, ordinarily, so as to give a true conception of the dip. (See pp. 175 and 176.)

At each well location a hole is bored with a drill press to a uniform depth, generally about five-eighths of an inch deep. The diameter of the hole and that of the peg should be the same. A satisfactory peg may be made of seasoned pine about one-half inch in diameter. All pegs should be the same diameter and length. These pegs or dowels can be turned out by a planing mill at reasonable expense.

A white print or blue print of a graphic log of each well on a scale of 100 feet to the inch is then cut just wide enough to wrap around the peg and glued onto the peg. The logs should be so pasted that the sea level or datum plane of each well lies in the same horizontal plane. To accomplish this the pegs should be marked a certain distance from the baseboard and the sea level or datum plane of each peg pasted opposite that mark. The datum plane established should be far enough above the baseboard to allow the well drilled deepest below the datum plane to come on the peg, except, perhaps, where there are one or two very deep test wells. Then the bottom part of the graphic log can be pasted at the base of the peg. The pegs should be long enough to show all formations penetrated by the well with the greatest surface elevation.

The pegs of different wells are placed in holes in the base according to their location. The formations or the principal oil or water sands are correlated by means of bright-colored threads running from well to well. Usually one definite marker is shown by means of a certain colored string. Irregular points of water shut-off can be shown by a thread stretched from well to well and fastened at each well opposite the water shut-off point.

Such a model shows the casing, formations, and perforations as shown on the cross section, and in addition shows the general broad structural features. Any special features, such as high water content in a well, can be noted at the base of the peg.

Plate V, *B* shows a wooden peg model of wells on a property in the Santa Maria field. This particular model brings out the dome structure of that field.

One of the larger oil companies uses small (one-quarter inch) aluminum or steel rods in place of wooden pegs. The rod is placed in a crude, lathelike apparatus in a horizontal position and rotated by an attachment to an electric motor. A scale of 100 feet to the inch rests parallel to the rod. In coloring the rods different water colors are used for different formations. Suppose, for example, the first 60 feet were black clay, and this formation was designated by black. The rod is colored black from 0 to 60 feet as follows: After dipping the brush in the black color it is held gently against the rotating rod at the zero point and moved in a straight line to the 60-foot point, as shown by the parallel scale. The coloring of the rod is completed by applying the proper colors in a similar manner for the scaled depths at which different formations were encountered in drilling.

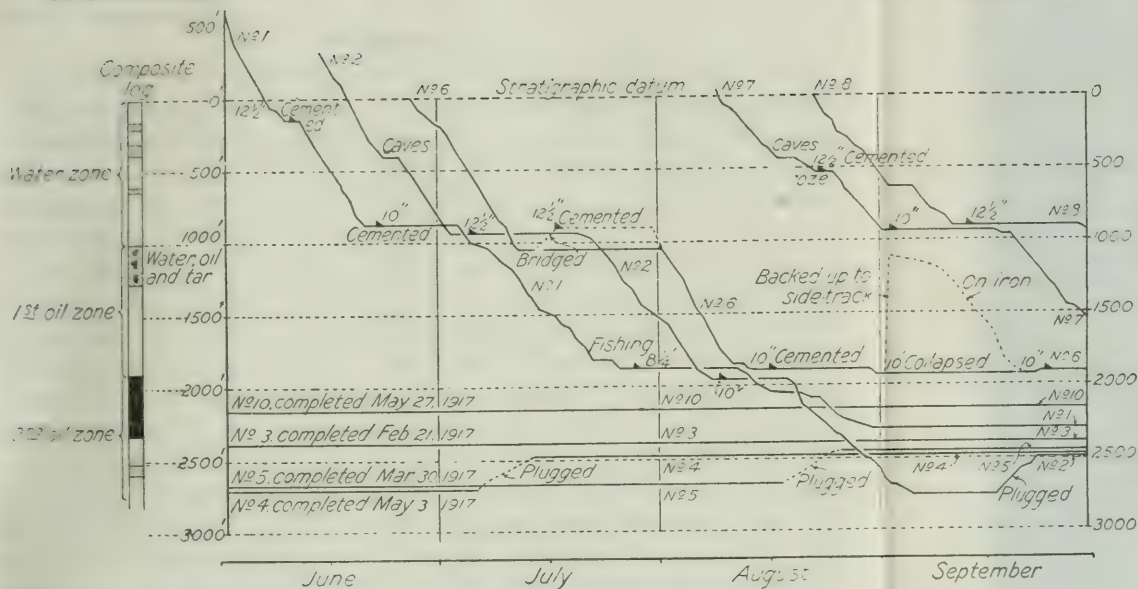
Unless the surface elevations of the different wells are equal, account must be taken of the datum plane so that when the pegs are set up, a plane passing through the datum or sea level of each peg will be horizontal. This may be done in two ways: First, color the pegs regardless of the well elevation, and then, in mounting the pegs, take care of the sea level; or, second, establish the zero point from the base of the rod before coloring in the formations. In the first case, the ends of the aluminum rod may be sawed off to establish the zero point in proper reference to the datum. In the second case, the scale of 100 feet to the inch, which rests parallel to the peg, may be movable so that the zero point can be shifted a certain distance from the base of the peg. For example, sea level may be established, say, at the point representing 2,000 feet as measured from the base of the peg, then with a well elevation of plus 650 feet, the zero point would be 26.5 inches from the base of the peg. (Scale assumed to be 100 feet to the inch.) The zero point can be shifted to this point and coloring of the rod started.

After the rods of different wells are colored, they may be placed in their proper location in the baseboard. If the pegs do not stand erect, they should be supported by a top board with well locations scaled to match those in the baseboard and with holes bored to receive the top of the peg. The top board should be held rigidly by wooden supports extending up from the four corners of the baseboard.

Correlation by colored strings is used as with a wooden peg model.

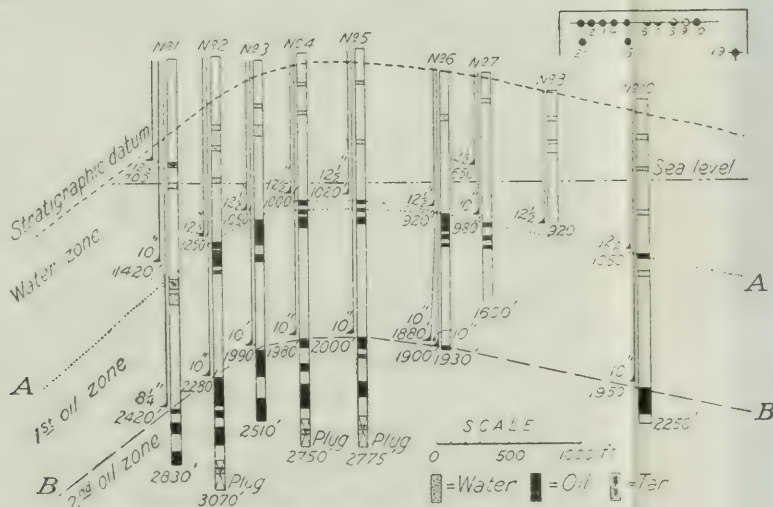
Garfias²⁴ has suggested a form of peg model that can be prepared rapidly in a district where the correlation is definite, such as the producing zone of the Tamasopa limestone in the Mexican fields. At each well location, shown by a map on the baseboard, a thin brad

²⁴ Personal conversation with V. R. Garfias, petroleum engineer, Empire Gas & Fuel Co., New York.



Depths below derrick floor
to stratigraphic datum

$N_{21} = 550$
 $N_{22} = 330$
 $N_{23} = 130$
 $N_{24} = 100$
 $N_{25} = 100$
 $N_{26} = 0$
 $N_{27} = 50$
 $N_{28} = 20$
 $N_{29} = 100$



PROGRESS CHART OF WELLS DURING DRILLING.

is driven so that the top is a certain distance above the baseboard. The distance of the brad above the baseboard, which is the datum plane, is determined by the scaled distance of the top of the oil zone above datum. The tops of these brads then represent the attitude of the oil-bearing bed.

STEREOGRAMS.

A stereogram is used to show the underground structure graphically and to bring out a general broad relationship. In actual underground study to determine the proper casing depths, well depths, etc., stereograms are of limited application, because they show three dimensions on a flat surface. Very little detail can be shown, as too many figures on a stereogram are confusing.

The particular value of stereograms is to show general results to the nontechnical man. Plate VI is a stereogram of the structure at La Salle, Ill., and vicinity. This stereogram shows the La Salle anticline and the stratigraphic sequence of the beds in that vicinity. Plate VII, a stereogram of the Birds quadrangle,²⁵ Ill., illustrates how a stereogram may be used to show the lenticularity of an oil sand.

A stereogram is prepared by laying off three ordinates, two at given angles to the vertical. In Plate VII the north-south ordinates are laid off at an angle of 60° to the east-west ordinates, and the north-south ordinates are 48° from the vertical. The angle of 60° between the north-south and east-west ordinates is often used, but there seems to be no special reason for using the angle of 48° between the vertical and north-south ordinates. Another system is to plot the east-west ordinates at right angles to the vertical and the north-south ordinates at 60° to the right of the vertical. The choice of angles is optional.

Once the angles are selected the location of the wells are plotted to true scale on the north-south and east-west ordinates, and the depth of the oil sand, or other data plotted according to its distance below the sea level or other datum. The datum plane is chosen at the start of the work.

Other models, such as geologic models, are prepared by representing in plaster or clay the surface of a particular bed. These are very showy, but hardly worth the trouble for underground work.

DRILLING PROGRESS CHART.

The operator can follow the progress of the drilling wells by means of a chart, on which interesting comparative data of the different wells can be shown; for instance, the time lost on fishing and cementing jobs; the slow progress in passing through cavey or hard formations; the comparison of drilling time between rotary and cable tools, etc.

²⁵ Rich. J. L., Oil and gas in the Birds quadrangle: Ill. State Geol. Survey, Univ. Illinois, Bull. 33. 1916. p. 132.

The chart most commonly used is similar to that shown in Plate VIII, except that the zero points representing the ground surface lie along a horizontal line rather than being located with reference to a stratigraphic datum. The depths of the various formations are plotted as ordinates and the different days of the month as abscissas. A customary vertical scale is 100 feet to the inch; in selecting the horizontal scale the engineer should choose a scale sufficiently large so as not to confuse the different wells by crowding. Where wells are at the same depth on the same date, different colored inks may be used to avoid confusion.

Another type of chart shows drilling operations with respect to a stratigraphic datum. This type has the advantage that the correlation may be used to predict easily what may be expected as drilling progresses. For example, if some wells had difficulties at certain stratigraphic depths, the operator would be on the lookout as corresponding depths in new drilling wells. Thus, Plate VIII shows that wells 2 and 7 lost time on account of caving formations about 400 feet below the stratigraphic datum. In later drilling wells, this information will serve as a warning. The objection to this type of chart is that in many new wells the location of the marker may not be known, and unless it can be closely estimated the plot of a separate well can not be definitely established until the marker has been located in it. In places, the marker can not be determined until the well has been drilled to within a few hundred feet of the oil sand.

This type of chart has been ably discussed by Collom,²⁶ and a copy of his chart reproduced in Plate VIII.

Extracts from Collom's discussion follow:

The chart here presented differs from those ordinarily used in engineering work in that it directly refers to distances from known strata rather than the ground surface. It therefore directly compares geological information with drilling and production data.

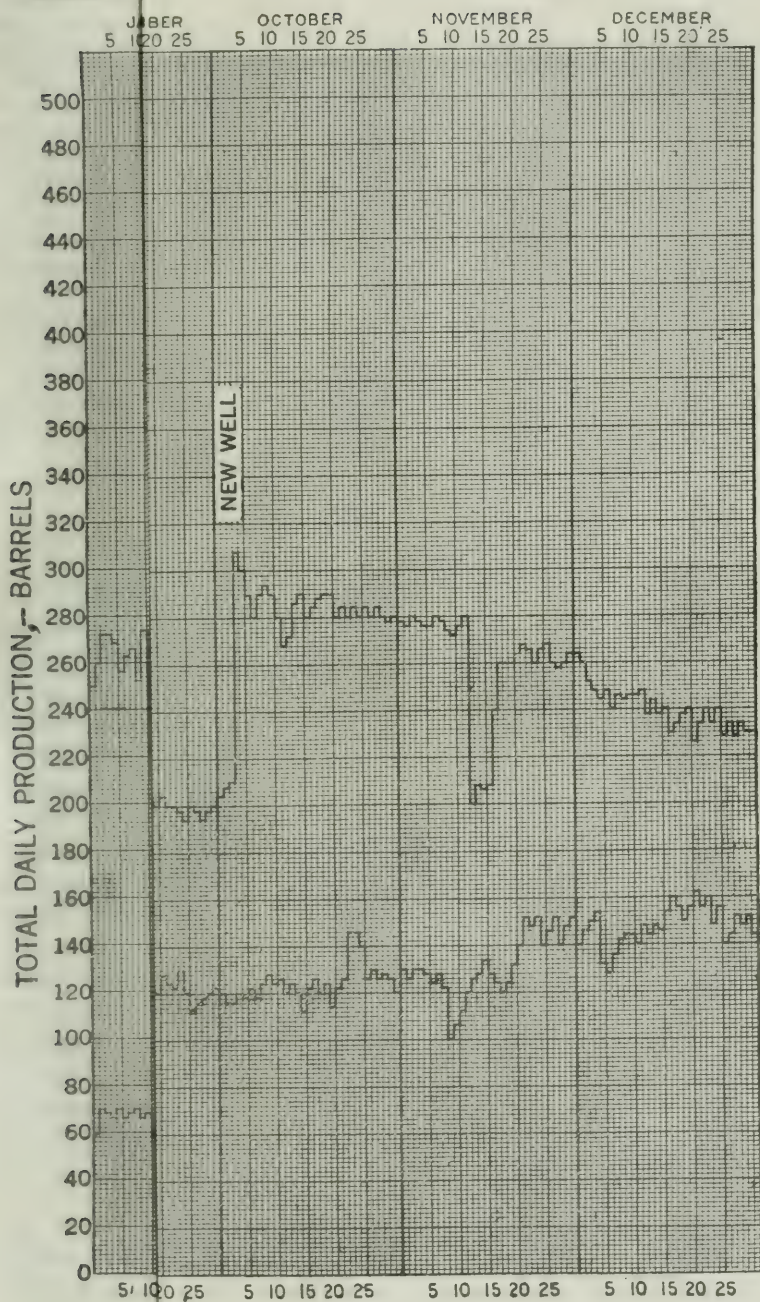
Referring to the accompanying cross section of a group of wells (Pl. VIII), it will be noted that a line of correlation "B" has been drawn across the top of the oil sands of the "Second oil zone." This line defines the stratigraphy of the formations.

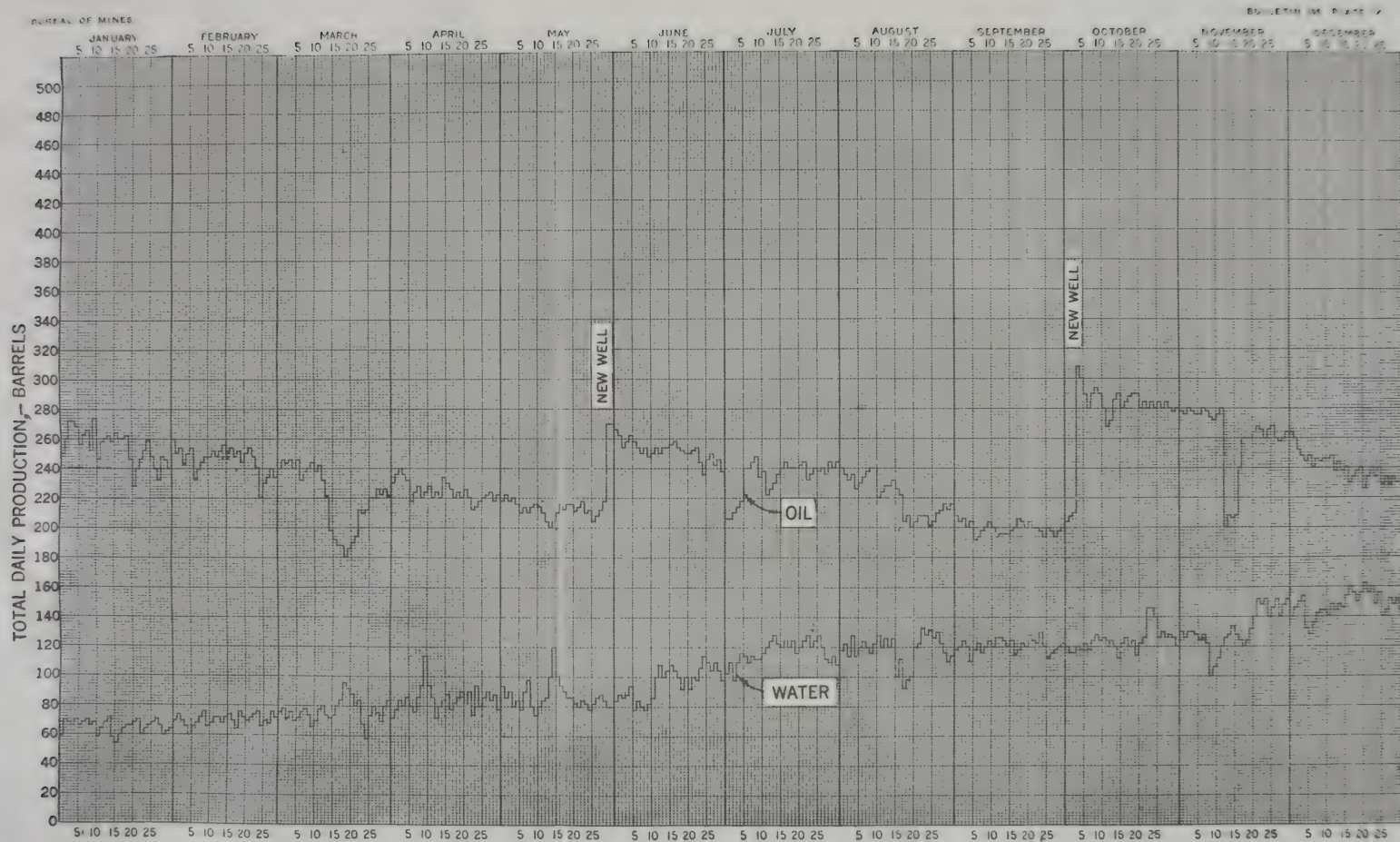
With the idea of presenting a graphic history of drilling operations with respect to the stratigraphy of the formations penetrated rather than the respective depths below surface, a line parallel to the line of correlation B (see cross section) is assumed at a position below which the essential depths drilled can be plotted. The distance between the line of correlation and stratigraphic datum can be chosen arbitrarily.

In certain localities where some definitely known stratum or formational marker exists * * * the line of correlation of this stratum in the various wells may be used as the stratigraphic datum.

When such stratum as the one referred to exists in a group of wells, one progress chart can be made for the entire group, irrespective of their location.

²⁶ Collom, R. E. Progress chart for comparison of a group of drilling wells: Bull. 84, California State Mining Bureau, 1917-18, pp. 196-197.





PLOT SHOWING TOTAL DAILY PRODUCTION OF OIL AND WATER, WESTERN OIL CO., 1916.

On the accompanying cross section the stratigraphic datum is drawn through zero depth—that is, the derrick floor at well No. 6—so that all corrections for differences from surface to stratigraphic datum in each of the wells will be plus. In this position, also, the drilling records with respect to the principal upper water strata and other formations of importance can be plotted.

The data on the progress chart are shown with respect to time and depth. A convenient vertical scale is 100 feet to 1 inch. The depths drilled per day here shown would be unusual for anything but illustration. Progress in drilling is plotted from the daily tour records. It is not necessary for plotting to figure corrections between depths below surface and depths below stratigraphic datum. A graphic scale may merely be placed in such a position on the chart as to automatically correct for the distance of the derrick floor above or below the stratigraphic datum line.

At the left end of the progress chart is a composite graphic log of formations between the stratigraphic datum and the bottom of the stratigraphically deepest well in the group.

All lines of correlation are horizontal on the progress chart. Drilling operations in any well, plotted as the work progresses, can be referred across the chart to the composite log for a check on the formational progress of the work.

GRAPHIC CHARTS APPLIED TO THE OIL INDUSTRY.

By C. E. SAMPSON,

Consulting petroleum engineer, Bureau of Mines.

In studying any problem composed of component parts represented by a great amount of tabulated figures, the average person finds it difficult to retain, during the investigation, the relative values of the different factors involved. Should the same data be presented in graphic form it becomes an easy matter to arrive at the correct conclusions; facts are forcibly impressed upon the mind and the mental picture is more readily retained.

The oil industry has offered a good field for the application of charts; in the last few years they have been used with much success in making clear to the operator the existing conditions on his particular property.

Much of the data shown in Plates IX to XIV were prepared by the writer in cooperation with R. A. Sperry—formerly superintendent of production, Gypsy Oil Co., Wichita, Kans., and now assistant general manager, Texas & Pacific Coal & Oil Co., Thurber, Tex.—in order to point out readily and forcibly the most salient features necessary for the proper operation of wells and properties in the Mid-Continent fields.

DAILY WELL PRODUCTION OF OIL AND WATER.

Plate IX shows a chart that is commonly used in plotting the daily production of oil and water from a well.

This curve is plotted on a form having the months and days of the month ruled in. It can be used to represent either the total daily

production of a number of wells or of an individual well, and in either case it brings out very clearly any increase or decrease in the production. From Plate IX the reader can readily see the change that has taken place by bringing in new wells, May 30 and October 4; also the length of time required for these wells to reach their settled production.

The chart shows that it was necessary to drill these two wells to maintain production, and also shows a gradual increase in the production of water from 60 barrels, January 1, to 144 barrels, December 31. This method of charting oil and water production has brought out some interesting facts: one example occurring in the Midway field, California, where it was found that the action of a well on one property directly reflected in the production of several wells on an adjoining property.

AVERAGE DAILY WELL PRODUCTION OF OIL AND WATER.

A method of charting individual wells on a small property is shown in Plate X. The average daily production of oil in barrels is represented in solid black by the column on the left of each pair, the other column shows the production of water. These figures are based on a full month's operation, so that the "lost-time" curve drawn across the top of the chart should explain any reason for a decline in production of oil other than water trouble.

By use of the legend and the days of the month, as shown at the top of the chart, the lost-time curve shows the date of shut-down, number of hours idle, and the cause of the trouble. For example, on February 6, the well was off 8 hours pulling rods (1 in legend, indicates "pulling rods"): on February 17, 12 hours repairing engine (6 in legend, indicates "repairing engine").

In July the water production had so increased that redrilling to shut off bottom water was necessary. The work of redrilling (4 in legend) was started August 1 and completed August 31. The mass curve of production shows that after cementing, the water gradually decreased and the oil increased, indicating that the water was shut off.

DAILY WELL PRODUCTION AND TROUBLE CHART.

Several of the advantages of graphic representation would be lost in applying the method shown in Plate X to a property having a large number of producing wells. To take care of such a condition the chart in Plate XI was devised. This chart shows for each day the number of wells producing, total amount of oil produced, the cause of any particular well being idle, and the time lost from the delay. The daily deliveries to the various pipe lines and the fuel oil consumed were also charted.

JANUARY
5 10 15 20 25OCTOBER
5 10 15 20 25NOVEMBER
5 10 15 20 25DECEMBER
5 10 15 20 25

LEGEND

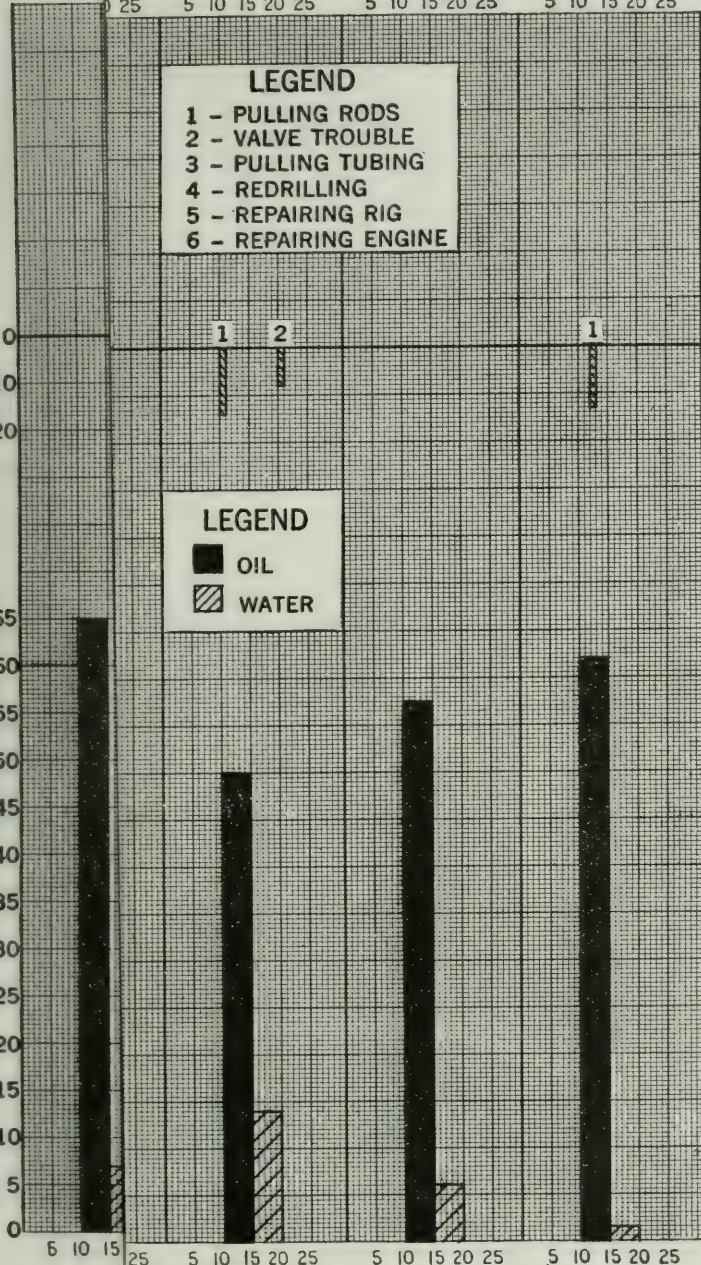
- 1 - PULLING RODS
- 2 - VALVE TROUBLE
- 3 - PULLING TUBING
- 4 - REDRILLING
- 5 - REPAIRING RIG
- 6 - REPAIRING ENGINE

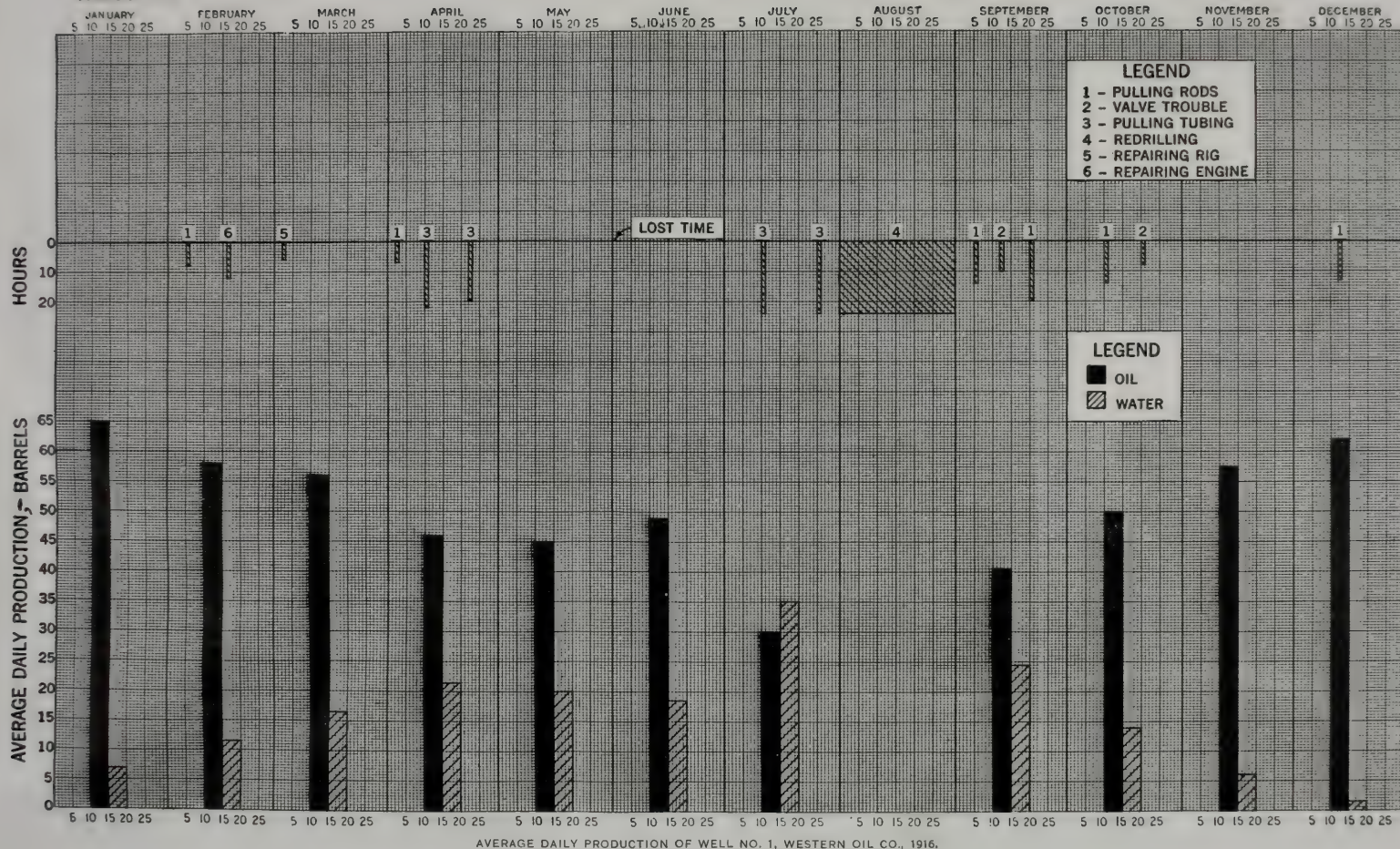
HOURS

LEGEND

- OIL
- ▨ WATER

AVERAGE DAILY PRODUCTION, - BARRELS





At the top of the chart, the horizontal column "Number of wells producing," designates for each day the total wells that are considered producers. In this example 20 wells were considered for the entire month of 31 days, although several were off 24 hours at a time owing to troubles.

Directly below the column "Number of wells producing," is the horizontal column "Days," each day being divided into 4-hour intervals by the "Hours" column beneath. On the left side of the chart are the three vertical spaces—"Well No.," "Total daily shipment," and "Total daily production." The well numbers in this property range from No. 1 to No. 25, inclusive. The scales used for production and shipments were the same, because shipments were made daily or as fast as the oil was produced.

The columns "Total daily shipment" and "Total daily production" show at the bottom the fuel oil consumed, scale from 0 to 125 barrels per day; from that point up, the scale shows the barrels per day shipped and produced, from 600 to 3,500. In applying this chart to a particular oil property, naturally the scale is adapted to take account of the conditions and changes in the property. The figures change from month to month, and it may be advisable to leave these columns blank so that they may be filled in each month to take account of any marked variation.

In order to permit a single tracing of the chart to apply to several properties, it should be so prepared that it can be filled in according to the needs of any property. For that reason, the engineer should leave blank, on the original tracing, the following columns: "Well number," "Total daily shipment," "Total daily production," "Number of wells producing," "Total lost time," and the various subheadings under "Recapitulation." Then white prints may be made of the original tracing, and for each property the columns can be filled in according to the conditions on that property.

In charting the curves of production and deliveries, colored pins were used to designate the actual amounts in the coordinative portion of the chart, then lines were drawn with similar colored crayons to connect corresponding pins. Although not shown in Plate XI, in actual practice a line was drawn across the chart showing the average daily production for the preceding month. This permitted a comparison of the operations of the past and current months. An additional curve was also drawn showing the total shipments for each day.

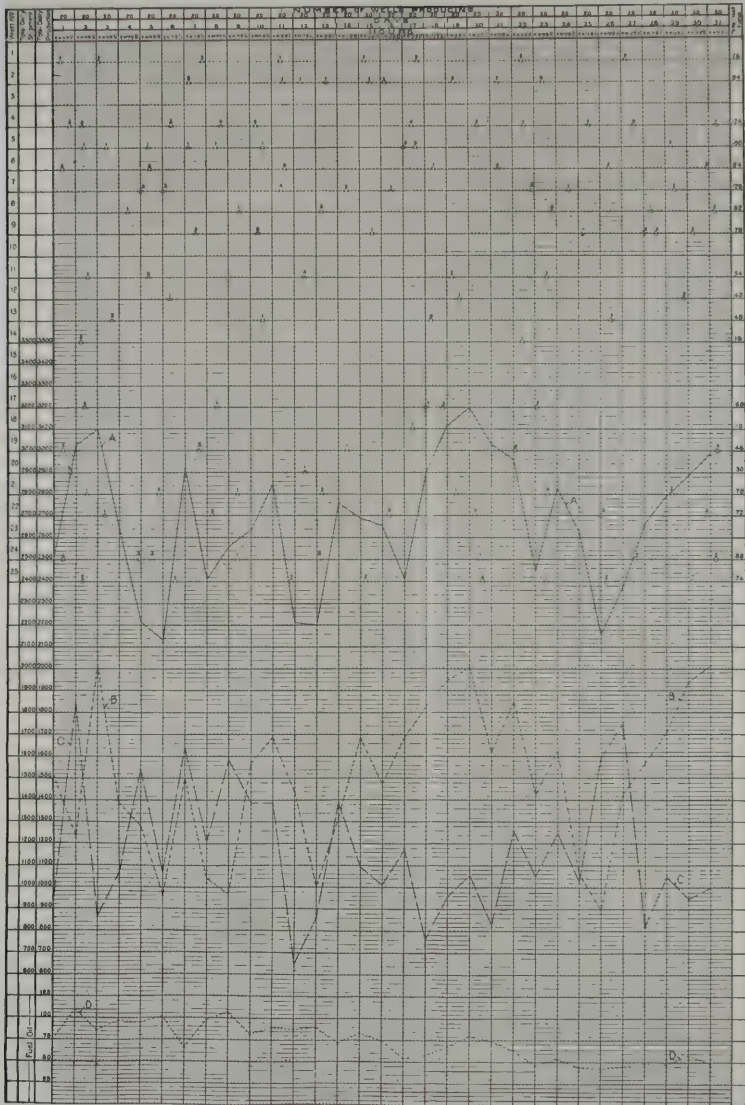
In Plate XI, curve A represents "total daily production;" curve B, "deliveries to Gulf Pipe Line;" curve C, "deliveries to Prairie Pipe Line;" and curve D, "fuel oil consumed." Total daily shipments are not shown in this chart.

TABLE 1.— *Distribution of lost time on 25 wells.*

[This table accompanies Plate XI.]

Cause.	Hours lost by well No. —																									Total hours lost.	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25		
Parted rods.....	18	52		32	56		26	30	14		28	22	14	10			12	10	10	12	32	8			16	424	
Engine trouble.....	12	8		10	6	30	20	6	6		6						2	2		6	12	14		22	20	158	
Pulling tubing.....	36			42	38	22	70	20	38			20	16				44		16	18	20	44		34	20	498	
Changing cups.....				10		8	10				12														10	14	64
Balls and seals.....	6			10					12		8								18		14				10	14	60
Repairs and additions to rigs.....		10		20		14							12				10				14						76
Belt trouble.....	4	8				10		6	8				6	6					2			6				4	58
Miscellaneous.....		6																							2	22	22
Total.....	76	84		124	100	84	126	62	78		54	42	48	16			68	10	46	30	78	72		88	74	1,360	

	1000	1000
	900	900
	800	800
	700	700
	600	600
	125	
	100	
Fuel Oil	75	
	50	
	25	



DAILY WELL PRODUCTION AND TROUBLE CHART.

(Size 41 by 54 inches)

To represent the daily lost time of each well, flat-headed tacks with numbers on the heads were employed. The list of troubles that were encountered is shown in the upper right-hand part of the figure. A tack with the number 1 on the head represents "parted rods," 2 "engine trouble," etc., each cause having a designating number as shown.

To explain the application of these tacks the case of well No. 1 will be considered. In the vertical column designated day 1, on the horizontal line representing well No. 1, a tack numbered 1 is located on the hour subdivision 8. This signifies that well No. 1 was idle 8 hours on the first of the month owing to cause 1, namely, "parted rods." On the 3d day of the month, a tack numbered 2 (indicating cause 2, or "engine trouble") is placed midway between the hour subdivisions 0 and 4, showing a shutdown of 2 hours on account of repairs to the engine; on the 7th, 20 hours were lost from pulled tubing; on the 11th, 10 hours were lost owing to rod trouble again; on the 15th, 6 hours were lost from changing balls and seats; on the 17th, 16 hours were lost pulling tubing; on the 22d, 10 hours were lost owing to engine trouble; on the 27th, 4 hours were lost owing to a broken belt.

On the last day of the month the total time lost on each well and the total hours lost owing to each particular cause were recorded. In this case the total lost time during the month was 76 hours (see Table 1).

The total lost time of well 1 due to parted rods, as represented by pin 1, was 18 hours; lost time due to engine trouble, as represented by pin 2, was 12 hours; lost time due to pulling tubing, as represented by pin 3, was 36 hours, etc.; the total lost time of well 1 for that month was the summation of these figures, or 76 hours. These figures were afterwards used in making up the distribution sheet shown in Table 1. The total lost time for each well during the month is shown at the right-hand side in the vertical column, "Total lost time."

To obtain the number of barrels of oil considered lost, the following method was used.

The diagram shows a total of 1,360 hours lost, which, divided by 24, gives 56.7 days lost. The 20 wells on this property should have had, for 31 days of this month, 620 producing days, but, owing to lost time, this figure was reduced by 56.7, so the actual number of producing days for the wells on this property was 620 minus 56.7, or 563.3. During the actual producing days the wells produced 83,117 barrels of oil, hence the average number of barrels per well per producing day of 24 hours was 83,117 divided by 563.3, or 147.6 barrels. Then 147.6 times 56.7 (lost time) gives 8,370 barrels of oil

lost, owing to shut-downs. This figure of 8,370 was then apportioned to the various causes, such as parted rods, engine trouble, etc. The actual barrels lost, according to the figures in the "per cent of total lost time" column is 31.2 per cent times 8,370, or 2,610 barrels lost due to parted rods; 11.6 per cent times 8,370, or 975 barrels lost due to engine trouble, etc.

The foregoing is not the most accurate method to employ, but is shown in order to demonstrate means of obtaining the desired information from properties wherein accurate gages are not kept of the daily production of individual wells.

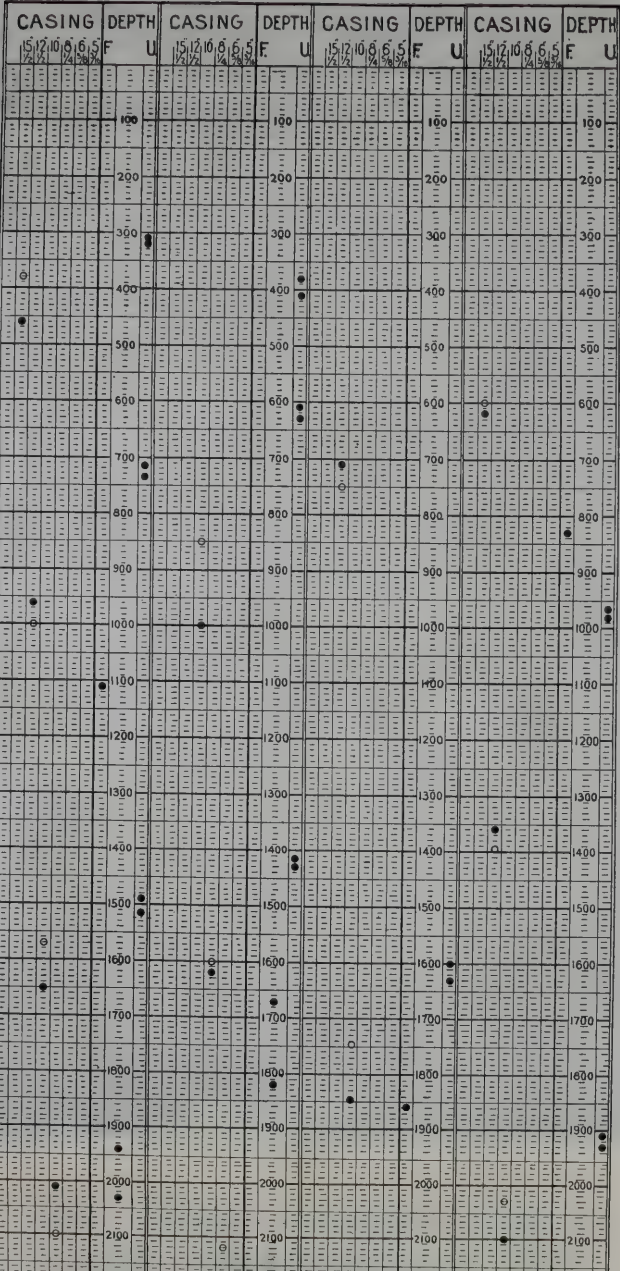
It is unfortunate that this latter condition does not prevail. Instead most operators are satisfied with a gage of the well that requires but a few minutes to obtain and which more than likely does not give a true statement of the production of oil and water.

Where accurate individual well productions are obtained, the computations for the lost-time chart are made on the basis of the average daily production of each well separately, and the total barrels lost is the summation of the barrels lost for each well.

It can readily be seen how continued delays on any one well will immediately stand out. The results of efforts to rectify these troubles can be closely watched on such a chart. The data used in demonstrating this chart have been assumed in every case, but in the application of the chart to actual conditions as found in the Eldorado field (Kans.), a considerable improvement in operating conditions was effected. Much trouble had been experienced with sucker rods, owing to water conditions, but this was cut to a minimum by closely watching on the chart the wells producing with old strings of rods and noting the results of installations of new rods of different makes. A comparison was made of the operations of the various makes of oil and gas engines and the different brands of belting used at the different wells.

After each chart was completed for the month, a photograph was taken; the 12 prints for each property were made into a panel giving continuous curves of progress for the year's work.

Correct knowledge at all times of the drilling progress is of similar importance to a thorough understanding of pumping conditions on a property or properties. To obtain the desired information it is necessary to refer in a great many cases to field reports, office statements, and logs, causing some confusion if a large number of wells are being drilled. Such a condition now exists in the north Texas fields where it is not an uncommon occurrence to find a single company running as many as 100 strings of tools.



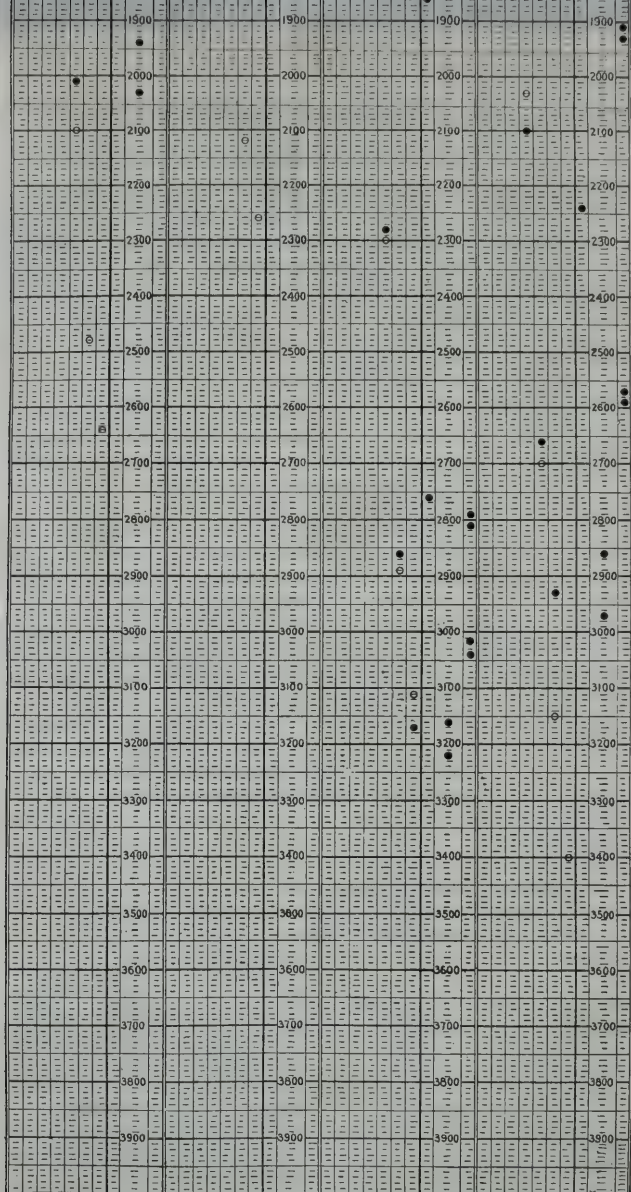


CHART FOR FOLLOWING PROGRESS OF WELLS AND CASING DEPTHS.

DRILLING WELL PROGRESS AND CASING DEPTHS.

The chart in Plate XII was designed to take care of the information obtained from about 30 drilling wells, but is flexible enough so that three or four times that number can easily be handled by simply using more sheets. The original tracing for this chart was made to include four wells, as this seems to provide a flexible unit, that is, in case of three drilling wells on a property the chart would readily apply. For 20 drilling wells only five prints would be necessary.

In explanation of the chart, a description of the first well on the left—namely well No. 4, on the Enyart lease—will be given. At the top of each column are found cards, as shown in Form 2, giving information that is self-explanatory. The form for these cards is printed on heavy paper and the data filled in with a typewriter. After a well is completed, the cards are filed for future reference.

In Plate XII, under "Casing," are vertical columns representing the several sizes of casing that probably would be used ($5\frac{3}{16}$ -inch to $15\frac{1}{2}$ -inch, inclusive). When authority for expenditure (A. F. E., in Form 2) was made and the amounts of the different casings estimated, white-headed tacks (shown by circles in Plate XII) were placed in the proper columns to represent these amounts. During the time a string of pipe was being carried in the hole, a blue-headed tack (shown by solid black circle in Plate XII) was stuck in the column for that size of pipe, and moved downward as the casing progressed. This showed at all times the total amount of that particular size in the hole, the blue pin finally remaining at a point on the scale indicating the point of landing the pipe.

It was necessary on account of contract work to know how many fishing jobs were going on, also to know where underreaming was required, and the extent of this work. In the "Depth" column, black pins were stuck into the scale on the left, headed "F," to show the depths at which trouble was encountered that necessitated fishing. On the scale at the right, headed "U," two yellow pins showed the top and bottom depths at which underreaming took place. A tack in the center scale, midway between "F" and "U," showed the depth of hole.

There was authorized in well No. 14, Enyart, of Plate XII, the following lengths of casing: 380 feet of $15\frac{1}{2}$ -inch casing, 1,000 feet of $12\frac{1}{2}$ -inch casing, 1,570 feet of 10-inch casing, 2,100 feet of $8\frac{1}{2}$ -inch casing, 2,480 feet of $6\frac{3}{8}$ -inch casing, and 2,640 feet of $5\frac{3}{16}$ -inch casing.

On the last day shown on the chart the hole was 2,030 feet deep. On the previous day the depth was 1,940 feet, showing an increase of 90 feet for the last 24 hours. There was a fishing job at 1,110 feet, and underreaming at three different depths—namely, 310 to 320 feet,

715 to 735 feet, and 1,490 to 1,515 feet. The use of two pins for representing the distance underreamed permits showing a much smaller distance than is illustrated.

The amount of pipe in the hole was 460 feet of 15½-inch casing (80 feet more than authorized), 960 feet of 12½-inch casing (40 feet less than authorized), and 1,650 feet of 10-inch casing (80 feet more than authorized). The 8¼-inch casing had not been landed, but was being carried at 2,010 feet.

The chart could also be made to show pipe troubles, locations of important sands or other formations, or could be made to fit conditions peculiar to other localities. At the completion of any well or wells the pins can be removed and the same chart used again.

TIME-DEPTH REFERENCE CHART FOR COMPARISON OF DRILLING WELLS.

After a number of wells had been drilled in a certain district, an average was computed of drilling time, costs, and lost time. The chart in Plate XIII was computed from the data obtained from 13 wells. The log shown is an average for the district and was obtained by comparison of all the logs in a particular area. The average depth of a certain number of wells on the first, second, third, fourth, etc., day of drilling was used to plot the "curve showing average drilling time."

The drilling curve was used to compare the progress of any well being drilled in this locality with the average of those previously drilled. The various uses and features of the chart are self-explanatory: on any well the depth of casing compared to that of the average well is readily emphasized. For example, a well on the fourteenth day of drilling should be at least 1,250 feet deep if the speed equaled that for the average well drilled in this field.

DAILY RECEIPTS AND DELIVERIES OF CRUDE OIL.

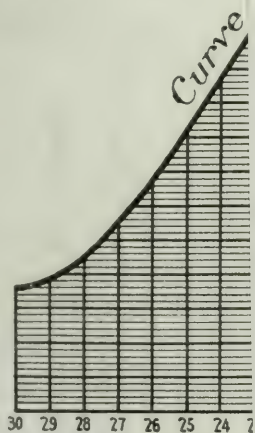
The chart illustrated in Plate XIV is used to show relative values of the receipts and deliveries of crude oil from a tank farm. It is seen from the mass curve that the receipts for the month are much greater than the deliveries. This is brought out more clearly by using colored crayons to designate the amount the receipts exceed the deliveries, or vice versa.

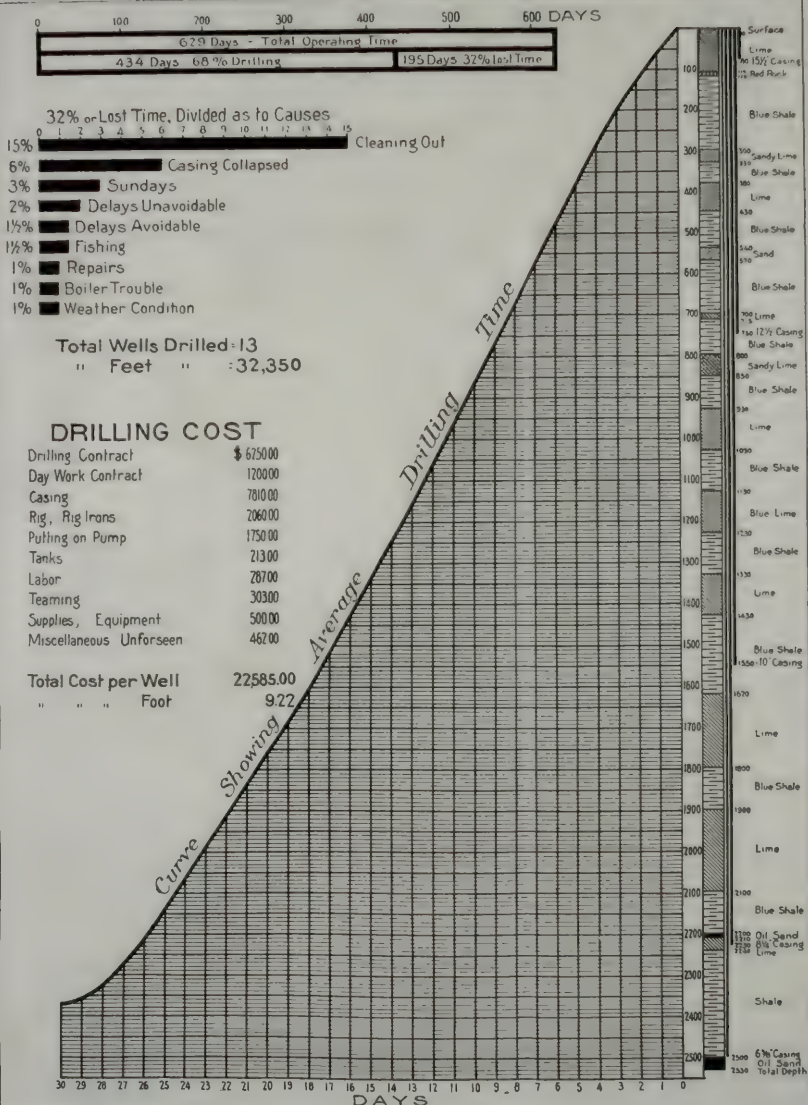
Two pins in the columns on the left of the chart give immediately, without referring to the curve, the number of barrels received during the present day, also the receipts for the previous day. On the right of the chart is shown by the pins the deliveries to-day and yesterday.

For example, the chart shows that on the 31st day, 8,275 barrels were received (as shown by the black circle in column "To-day")

Tanks
 Labor
 Teaming
 Supplies, Equipment
 Miscellaneous Unforeseen

Total Cost per Well
 " " " Foot





TIME-DEPTH REFERENCE CHART FOR COMPARISON OF DRILLING WELLS.

Form 2.—Cards used at top of chart (Pl. XII) for progress of wells and casing depths.

Lease, <i>Engart.</i> Well No. <i>14.</i> A. F. E., <i>B-209.</i> Date of location, <i>5-9-18.</i> Contract or company tools, <i>company.</i> Date started, <i>6-20-18.</i> Date completed, _____ Location of well, <i>150 N. and 150 W. of S. E.</i> <i>cor. Sec. 15, T. 12 S., R. 8 E.</i>	Lease..... Well No..... A. F. E..... Date of location..... Contract or company tools..... Date started..... Date completed..... Location of well.....	Lease..... Well No..... A. F. E..... Date of location..... Contract or company tools..... Date started..... Date completed..... Location of well.....	Lease..... Well No..... A. F. E..... Date of location..... Contract or company tools..... Date started..... Date completed..... Location of well.....
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under "Receipts," which is the same as "A"); 7,625 barrels the previous day (as shown in column "Yesterday" under "Receipts," which is the same as "B"). On the 31st, 5,750 barrels (see column "To-day" under "Deliveries," also same as "C") were delivered, while on the 30th day, 7,425 barrels were shipped (see column "Yesterday" under "Deliveries," also same as "D").

The main body of this chart shows the barrels of oil put in storage or withdrawn from storage each day. For example, on the 1st day of the month, 7,225 barrels of oil were received at the tank farm, and 5,950 barrels were delivered to pipe lines; the balance, 1,275 barrels, was placed in storage. This latter amount is represented by the set of cross-hatched lines referred to in the legend as "barrels put in storage." On the 2d day, 8,250 barrels of oil were delivered to the pipe lines, but only 6,775 barrels were received at the tank farm. This difference of 1,475 barrels was withdrawn from storage and is represented by a different set of cross-hatched lines referred to in the legend as "barrels withdrawn from storage."

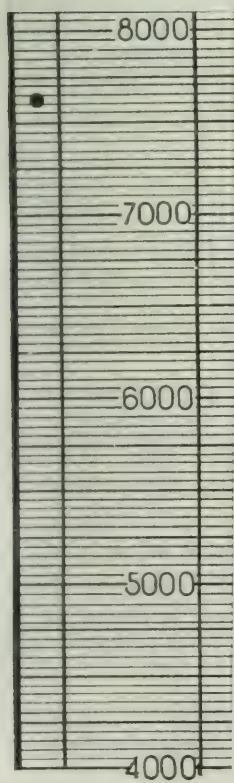
USE OF PINS ON MAPS.

The use of pins on maps, has been applied quite extensively in various industries to show certain facts. By means of colored pins on a wall map, the location of the wells on the different properties can be shown. Pins with various colored heads designate whether the wells are drilling, producing oil, a location, dry hole, producing gas or producing all water. This method is also an excellent one for showing the percentages of water produced by different wells in a large territory; wells producing 1 to 5 per cent water being represented by a certain colored pin; 5 to 10 per cent water, by another distinctive pin, and so on, taking in all the conditions available. In many areas it will be found that the pins of one color will be grouped in certain localities, immediately bringing to attention good or bad conditions of water as they exist.

NEED FOR A PRODUCTION ENGINEER.

The duties of a petroleum engineer, as outlined on pages 3 to 5, require constant familiarity with and understanding of the various operating conditions of different properties. This knowledge allows him to coordinate the various investigations and necessarily direct them to the point where they will be turned over to some branch of the organization for further detailed analysis.

Graphic charts provide a means of simplifying this work to such a degree that the data are before the engineer in a systematic, condensed form.



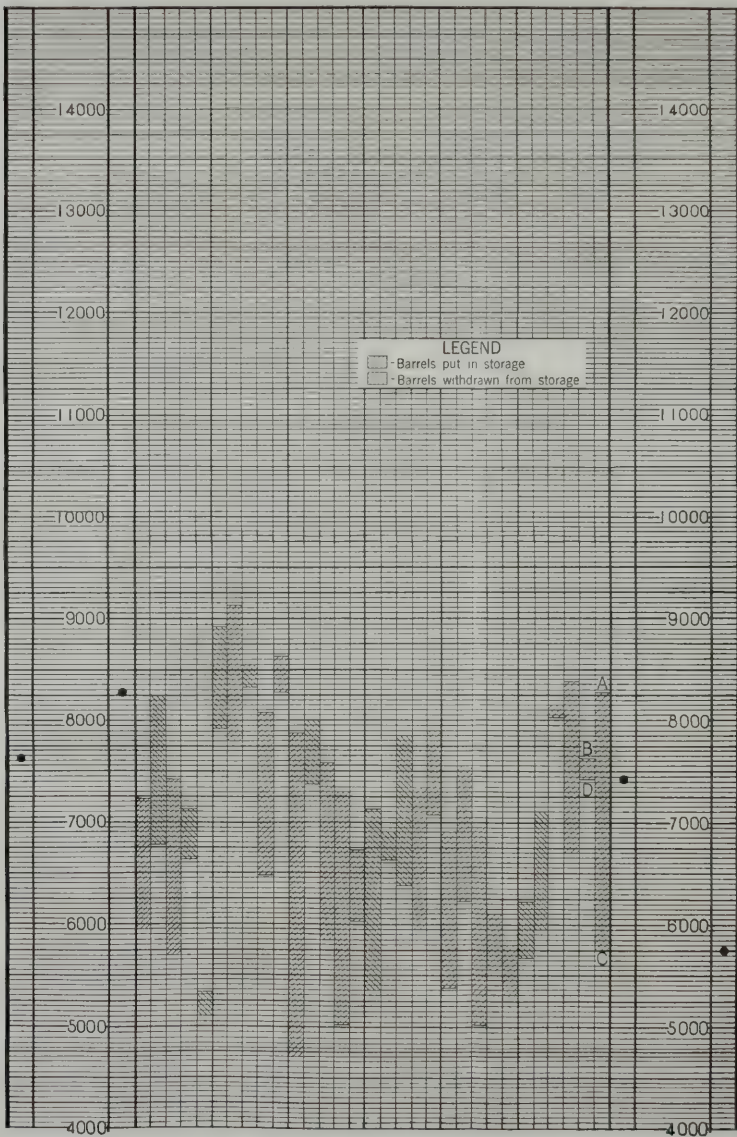


CHART TO SHOW DAILY RECEIPTS AND DELIVERIES OF CRUDE OIL.

APPLICATION OF UNDERGROUND STUDY TO OIL-FIELD PROBLEMS.

GENERAL REMARKS.

In preparing data by the methods discussed in the previous pages, many facts are learned regarding individual wells and the property in general. The engineer should not wait to complete the preparation of all data before he is ready to make recommendations. Considerable caution should be used at the start, however, because he must demonstrate to the nontechnical man the value of his work. His position is weakened by any mistake. More than that, some tests are very costly, and expensive tests should be made only after making sure that there is no information which will reveal the desired knowledge.

The problems are attacked by the use of the records, maps, and graphic data in conjunction with field tests. The use of the different material prepared is brought out in consideration of the various problems, namely, correlation of surface and underground geology; water problems; casing depths; underground losses; oil sands, location of productive sands, their thickness and quality of oil; well depths, new well locations, and extension of the field; future well production; shooting of oil wells; gaging of oil wells; perforations and setting of screen pipe; fluid levels and tubing depths; and methods for recovering more oil from the oil-bearing formations. These subjects will be discussed in the succeeding chapters.

CORRELATION OF SURFACE AND UNDERGROUND GEOLOGY.

When studying a property a reliable contour map showing the surface geology and structure of the field should be obtained or prepared at the start. The areal structure map serves as a valuable guide in predicting the attitude of the underground beds. Experience is showing more and more, however, that in flat-lying formations there are likely to be enough differences in the structure of the various horizons to make inferences based on the structure of the surface or even of another horizon unsafe. This has proven so in northern Texas. The structure of the particular producing sand is what is desired.

On the other hand, areal structure is often better than no guide, so in a newly developed field where the oil zone has been located, the

surface structure may be used to advantage to predict the most favorable sites for well locations, and as a guide in studying accumulations of oil, water, or gas. Without the surface geology as an indicator this sort of work may be materially handicapped.

On account of possible thickening and thinning of formations, overlapping, unconformities, etc., the engineer should consider carefully the underground correlation, so as to determine whether or not the surface and underground beds are parallel. If they are he can use the surface structure map to advantage until the property is fairly well developed. The surface geology is particularly important in undrilled territory, in which it serves as a basis from which to start.

As drilling proceeds it may be necessary to prepare a convergence map (see fig. 11, p. 51), but eventually structural maps of each important sand should be made if the beds converge.

WATER PROBLEMS.

GENERAL REMARKS.

The study and solution of the water problems is of paramount importance in some oil fields. The different water sands near the oil horizon should be definitely located, and an attempt made to prevent the premature flooding of oil and gas sands. Wells which are permitting water to flood the lower oil sands or permitting oil and gas to escape into the overlying porous formations should be repaired.

The evils of underground flooding are well known. In an area where flooding is going on the operator should give as serious consideration to it as he would to a destructive surface flood threatening to wash away his storage tanks. One of the most important protections against underground waters is to see that the wells are properly drilled, properly handled during production, and properly abandoned. The water problem thus becomes a most important underground study and it is given considerable attention in this publication.

The encroachment of edge water presents one of the most difficult problems to operators, for sooner or later it will flood the sand. Artificial methods, such as compressed air, should be studied for the purpose of retarding encroaching waters. (See pp. 75 to 78.) The location of wells should be carefully considered so as to obtain a maximum amount of the oil underground, and wells that are beyond recovery should be plugged off by the use of cement or mud-laden fluid to prevent other wells being ruined.

Even where a field has made water for a year or more, the operator should not consider remedial work impossible. Too often a field has been considered hopelessly lost, whereas in other areas similar conditions have been corrected by repair methods suggested by technical study. The possibility of repairing a well that had made water for a long time has been brought out by some corrective work in the Kern River oil field, California.²⁷ As a result of repairing one well the oil production of several wells was increased from 25 barrels a day to 59 barrels and the quantity of water lifted was reduced from 15,927 barrels a day to 240 barrels. This large amount of water was expensively lifted by two air-compressor plants. After the well was repaired, the air-compressor plants were no longer necessary, which eliminated an operating expense of \$500 per month and saved 100 barrels of fuel per month. The total job cost \$8,000. How much cheaper it would have been to have worked out the underground conditions at the start and corrected the wells instead of installing the air-compressor plants to lift the water. As stated by the California State Mining Bureau, "The success of the work is due to the fact that the investigation was carried out in a scientific manner by technically trained men."

Even though repair work may be started too late to save much of the oil that could have been recovered, the proper study of underground conditions will so direct future work as to appreciably lengthen the life of any field. Specific instances can be cited showing a saving of pipe, increase in production in individual wells where the water has been shut off, and reduction of pumping costs. The operator should not wait for the water to pump itself down, for in many wells where this has been tried the water was more abundant after a year's pumping than at the start.

Underground water may occur in strata above or below the producing zone or in the base of the oil stratum itself. Water in beds above or below the oil zone may be controlled by proper methods of drilling and casing wells, and by constructive repair work, but where the water and oil occur together, the water can at best only be held back temporarily.

The value of preventive underground work is often intangible, for it is difficult to tell what would have happened if water troubles had not been corrected. The life of a field may possibly be predicted by past performances, provided the field declines at a normal rate, but if a field once starts to "water," its decline may be precipitous. On the other hand, the careful study of water conditions

²⁷ Second Annual Report of the State Oil and Gas Supervisor of California for 1915-16: Calif. State Mining Bureau, Bull. 82, 1918, pp. 255-260.

TRAPPING OF OIL UNDERGROUND.

and the application of corrective measures in time may greatly prolong the life of the field.

Some interesting work to indicate the way in which oil may be trapped underground by flooding of the oil sands with water is being conducted by R. V. A. Mills, petroleum technologist of the bureau, who kindly furnished the photographs for Plates XV, XVI, and XVII. In connection with his studies on the underground occurrence of oil, gas, and water, and the rearrangements of these fluids during their extraction from the pay sand, Mills prepared containers with glass walls so that photographs might be taken. Water, oil, or gas could be introduced at will. The container was filled with lenticular bodies of fine sand surrounded by a coarse grained sand.

The relative arrangement of the fine and coarse sands, shown by Plate XV, is in the main two large lenticular bodies of fine-grained sand situated in the midst of a coarser sand. There is also a narrow layer of medium grained sand extending across the container near the top. The discoloration in the lower part of the picture is due to

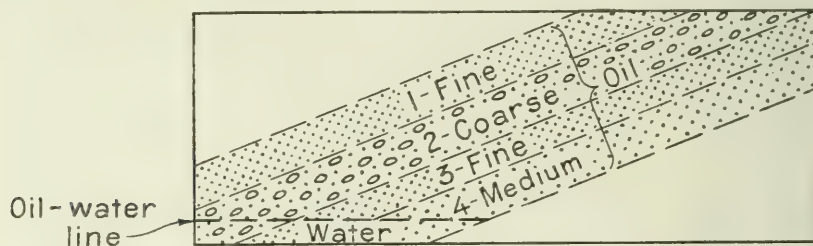
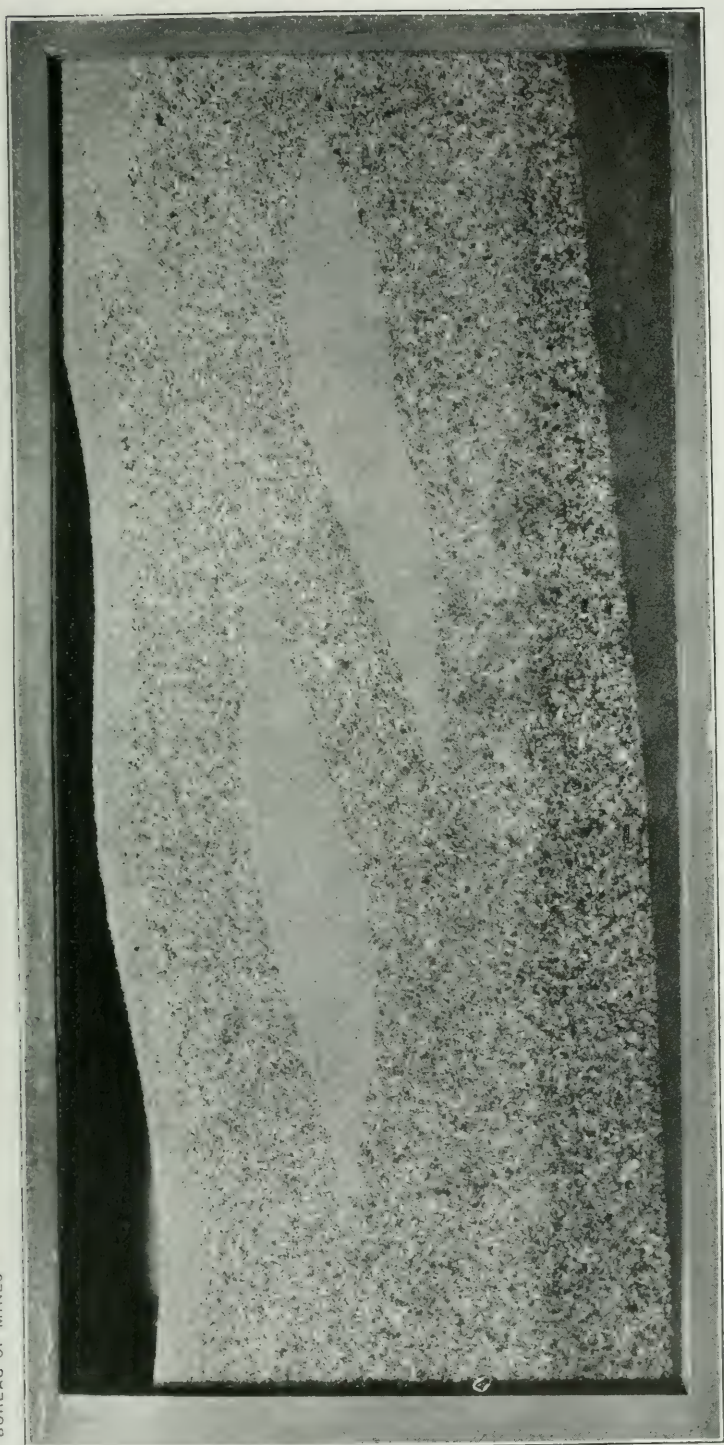


FIGURE 12.—Sketch to show sand texture and original relation of oil and water.

that part of the sand being saturated with water, the wet sand photographing darker than the dry sand above it. This picture was taken before the cap sand was added, which accounts for the black wedge-shaped band at the top, and before any oil was introduced.

The second picture, Plate XVI, was taken after the oil was introduced into the container. The water-saturated sand in the lower part of the container shows clearly, as it photographed much lighter than the sand saturated with oil.

Plate XVII (see p. 76) is a view taken after the container was flushed with water. The flooding was from left to right. The oil remained in the tight part of the sand, but was displaced by the water in the coarser part. This is brought out in the photograph, where the two main lenticular bodies of fine sand show as a darker color due to the presence of oil. The incomplete segregation of oil and water in the medium sand, at the upper part of the photograph, is brought out



CONTAINER SHOWING SAND BEFORE IT WAS SATURATED WITH OIL.
Two large lenticular bodies of fine-grained sand are surrounded by a coarse-grained sand.



CONTAINER AFTER SAND WAS SATURATED WITH OIL EXCEPT LOWER PART WHICH WAS FILLED WITH WATER.

Oil shows as black, water light.

by the dark and light spots, indicating mixed pockets of oil, water, and air. These pictures show many other interesting data which will be brought out by Mills in a later paper.

Mills found that in the fine sand, water slowly displaced the oil which moved upward into the coarse sand and there segregated above the water. In time, a large part of the oil that was retained in the fine sand would thus migrate into the coarse sand. However, under ordinary field conditions it is doubtful whether the operator would benefit, because the exchange between oil and water in fine tight sands is very slow. During the time that the exchange is taking place, the pumping of excessive quantities of water with relatively small quantities of oil would make operation of the wells unprofitable. The effects of the exchange are not felt until the damage has been done through hydraulic flow of the water through the more open parts of the sands. In other words, there is at first sight a rapid movement

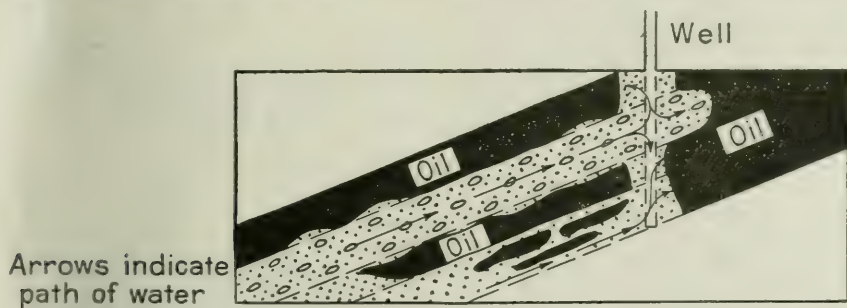


FIGURE 13.—Sketch to show how fluid advances most rapidly through the coarse sands and the water thus traps the oil in the fine tight sand. There is incomplete segregation of oil and water in the medium-grained sand (No. 4 in fig. 12).

along the paths of least resistance under the laws of hydraulic flow of liquids, followed by a readjustment under the laws of capillarity.

Figures 12, 13, and 14 are hypothetical sketches to show how fluid advances most rapidly through the coarse sands and thus leaves behind oil in the fine tight sand, much of which is eventually lost beyond recovery. In figure 12 the texture of the different sands is shown. In figure 14 the original water line is shown by the solid line; in figure 13 the water has advanced through the coarse sand No. 2 to the well; this is shown in figure 14 by the dashed line marked 2. In its flow through sand 2 the water invades slightly at times the fine sands 1 and 3, which is shown in figure 14 by the dashed line marked 1 and 3, near the original edgewater line. The water passing up through sand 2 enters the well and forces its way a short distance into the finer grained sands 1 and 3. The water working into the sands from the well is shown in figure 14 by the dashed lines circling the well.

The water invades the medium sand 4 more readily than the fine sand, but does not penetrate as far as it does into the coarse sand. The water reaches the well through sand 4, although there is an incomplete segregation of oil and water in which bodies of oil are trapped as shown in figure 13. This water line is shown in figure 14 by the dashed line marked 4. Even in the coarse sand 2 the water does not flush all oil from the sand, as figure 13 might indicate.

OBJECTIONS TO WATER.

It has been claimed that water helps "flow" the oil to the well, and that ²⁸ "the continuous entrance of relatively small quantities of water through leaky seed-bag packers in the early days of the

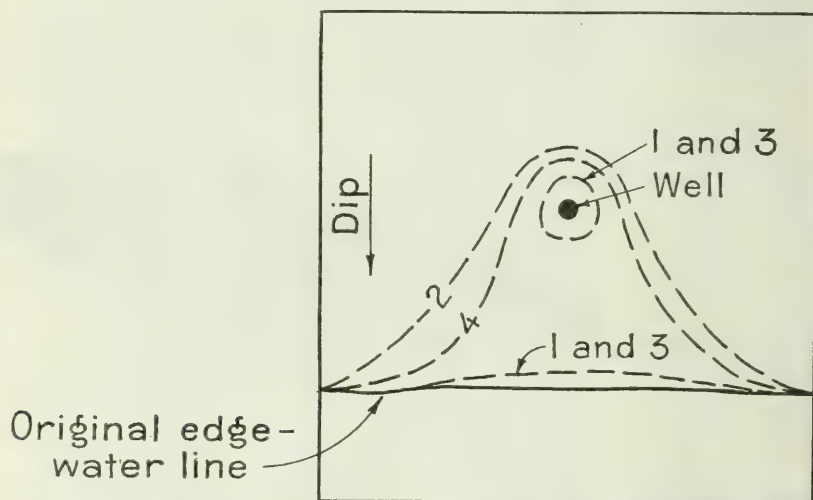


FIGURE 14.—Surface plot to show advance of oil-water contact lines through sands of different texture. (See text.)

Pennsylvania field may have furnished the means necessary to prevent the chilling of the oil that was expelled through the free escape of large quantities of gas. The water so entering may have accounted for the continued productiveness of some wells, preventing the chilling of the oil and the formation of waxy sediments, and have been one of the factors in some of the phenomenal productions of that period."

It has thus been advocated that the presence of a small amount of water under certain conditions is beneficial; but those cases that prove beneficial will undoubtedly be very exceptional. The writer believes that the operator should make every effort to keep the water out of the oil sands, and out of the wells. To accomplish this it is

²⁸ Huntley, L. G., Possible causes of the decline of oil wells: Technical Paper 51, Bureau of Mines, pp. 20-21.

advisable to drill the wells in such a manner that they stand as permanent monuments during the probable life of the field. If the wells are drilled properly in the first place much of the repair work later on will not be necessary. Experience has shown that it is usually folly to attempt to exhaust the water from the sands and the simplest way is to exclude the water from the hole.

Too often do we see articles in trade journals to the effect that water is ruining a well. The following is quoted from the *California Oil World*, July 10, 1919:

Santa Fe Springs, July 9.—Water has broken in on the Union's Meyer well, and the successful outcome hinges on the ability to shut off deep water.

Hardly had the well gotten under way producing when a quantity of water made its appearance. At first the water was regarded as of little consequence, but it gradually increased until now the well is making only 50 barrels of oil and 200 barrels of water. An attempt is to be made at once to trace the water and shut it off, but as it seems that this water is coming from an area close to the oil sand, some doubts are being entertained as to the success of making a shut-off. If the water can be cemented off, the company has a wonderful well that should be capable of making more than 1,000 barrels of the lightest oil ever produced in any quantity in southern California.

If the water can not be taken care of, the well is a failure.

The Union Oil Co. did not lose faith in the possibilities of shutting off the water, as was shown by the following article in the *California Oil World*, August 14, 1919:

Santa Fe Springs, August 13.—Indications are now strong that the Union Oil Co. has made a successful shut-off of the deep water in its 4,600-foot Meyer well at Santa Fe Springs. The well is now flowing through a one-fourth-inch opening and is making 40 to 50 barrels a day of oil free from water. It is believed that through a larger opening the production will greatly increase. However, the well will be watched closely for several days to assure the success of the deep cementing job. Success in handling the water situation in this well means a 33° gravity oil field for southern California.

Another example is quoted from the *Oil Weekly*, April 26, 1919.

Production at West Columbia has been cut in half during the past seven days by salt water coming into wells or by wells stopping their flow in some cases because of salt water. Last week the daily average production on Thursday was approximately 32,000 barrels. This week on Thursday the production was 16,200 barrels.

Practically every company having production at West Columbia has been affected. Last week the production of the Crown Oil & Refining Co. was 8,000 barrels. This week it had dropped to 3,000.

The work done by the Empire Gas & Fuel Co.²⁹ in plugging off bottom water in the Augusta field, Kansas, has accomplished successful results.

²⁹ Shidel, H. R., Cement plugging for exclusion of bottom water in the Augusta field, Kansas: Trans. Am. Inst. Min. Eng. 1918. pp. 1613-1620.

Remarkable results were accomplished by the producers in the Cushing field, Oklahoma, where they, in cooperation with A. A. Hammer and B. H. Scott, of the Bureau of Mines, successfully cemented off bottom water. After a careful study it was decided that water was coming from bottom. The water was shut off by the use of cement. The following statement indicates the results accomplished on 146 wells: Before cementing, the yield of oil was 412 barrels per day, and of water, 7,520 barrels; after cementing, the yield of oil rose to 4,716 barrels a day, and that of water dropped to 628 barrels, an increase of 4,304 barrels of oil and a decrease of 6,892 barrels of water. Not counting the decreased cost in lifting less water, the value of the additional oil recovered in a year, at \$2.50 a barrel, may be estimated as 4,304 times 365 times \$2.50, or \$3,927,400. The production, of course, would not continue at the same rate, but even if the savings were decreased by 50 per cent they would still amount to almost \$2,000,000 in a year.

In this work the correcting of water trouble in one well shut off the water in a well located about 1,300 feet distant. This adjoining well previously made 20 barrels of oil per day and a large quantity of water, but after the neighboring well had been repaired the second well came back, making 600 barrels of oil per day.

Of course, there are many areas where the most detailed underground study and mechanical work can not entirely prevent water trouble, but it has been shown time and again that such work followed by corrective measures improves water conditions and in certain instances has prevented the flooding of the sands. It is only good business to spend money for such work when one considers the amount of good that may be accomplished by a comparatively small expenditure. Certainly such a destructive agent as underground waters deserves special attention.

The prime necessity of mastering the underground water problem is, of course, to prevent water entrapping the major portion of the oil still underground. On the other hand, even if this point were entirely disregarded, there are sufficient reasons to warrant a study of water problems and subsequent repair work. Water is objectionable because its presence in appreciable amounts means:

1. The ultimate loss of thousands of barrels of oil which may be trapped underground.

2. The loss of casing-head gas.

3. The increased lifting cost, as wells producing water cost more to pump, and in such wells the life of the tubing, pump and sucker rods is shorter, and there is no additional cost for the replacement of corroded pipe lines and fittings.

4. The possibility of water flooding the sands and driving the oil to a neighboring property.

5. The forming of emulsion, which necessitates expensive dehydrating towers to separate the oil and water. (See fig. 15.)

The effect upon production of an encroaching edgewater is shown in figure 15. The rapid decline of oil upon the appearance of water is plainly shown in the figure. As the flow channels are opened, the quantity of water generally increases. In many wells, the water will reach some set production, such as 250 barrels a day, and produce steadily at that rate. Very often the quantity of water made may be limited by the pump—that is, a certain size pump will handle a limited amount of water. The operator should not think he is pumping out all the water that comes in, for much of it may be working back into the oil sands and doing damage.

An oil sand flooded with water does not lend itself to future recovery by means of compressed air or other processes; furthermore,

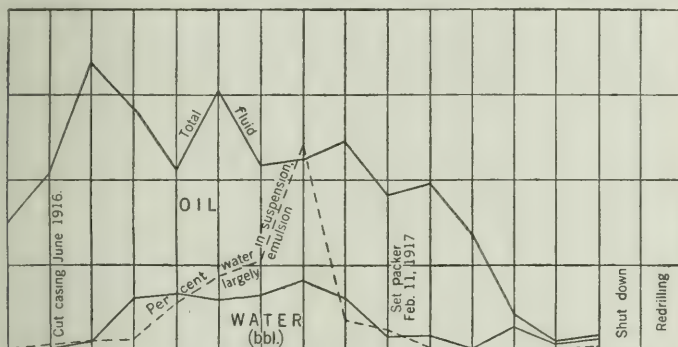


FIGURE 15.—Plot showing increase of water in suspension and emulsion, in addition to an increase of free water, upon appearance of water in a well.

there is a loss of production during the various shut-downs for changing worn-out pumps and for pulling rods.

LIFTING WATER BY COMPRESSED AIR.

The application of compressed air to lift water from oil wells has proved to be expensive, and in many wells is made unnecessary by shutting off the water. E. W. Wagy,³⁰ petroleum technologist of the bureau, reported unfavorably on this method as practiced in California. Extracts from his report follow:

The operators tried to exhaust the supply of water by the installation of air compressors instead of repairing the wells. To them this appeared to be a method of last resort. * * *

If there is any real advantage to be credited to this method it is in cleaning out wells. * * * With a sufficient pressure and quantity of air, it is a very efficient and quick means of taking out sand, provided, of course, that there is

³⁰ Wagy, E. W., The use of compressed air in California for producing mixtures of oil and water: Unpublished manuscript, Bureau of Mines.

plenty of water present to help transport the sand. In fact, one operator, Mr. J. A. Pickle, of the Jewett Oil Co., McKittrick field, California, made use of air to clean out wells which he could not clean out with the ordinary bailer. The writer also had satisfactory results in cleaning out with air. In one well, where the casing was bad, the sand would run in as fast as it could be bailed out, while

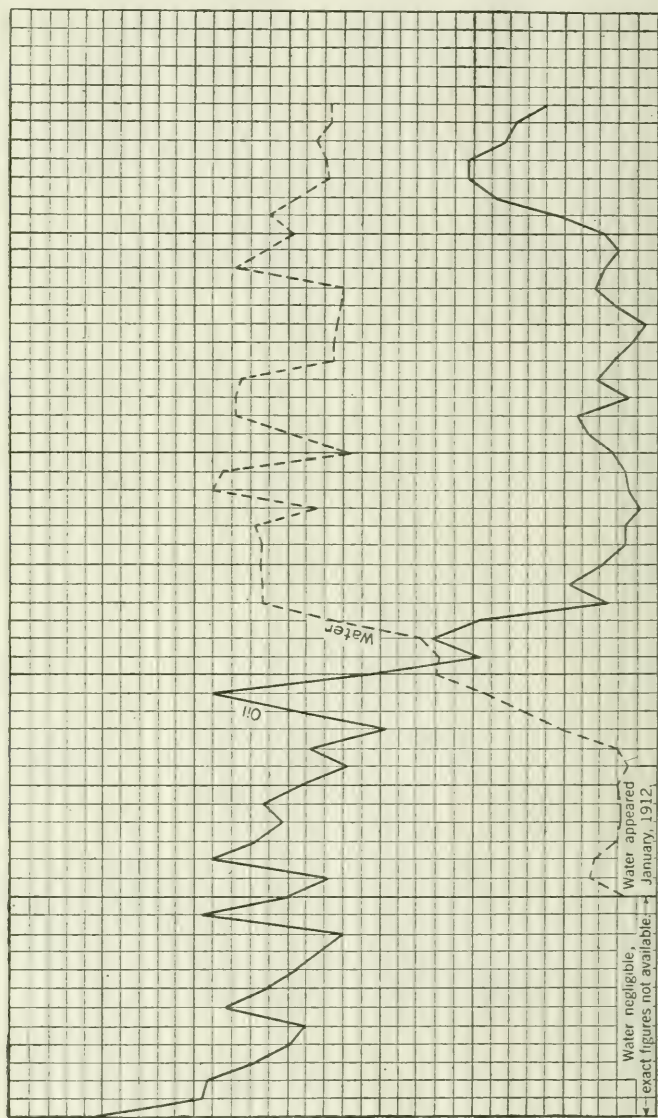
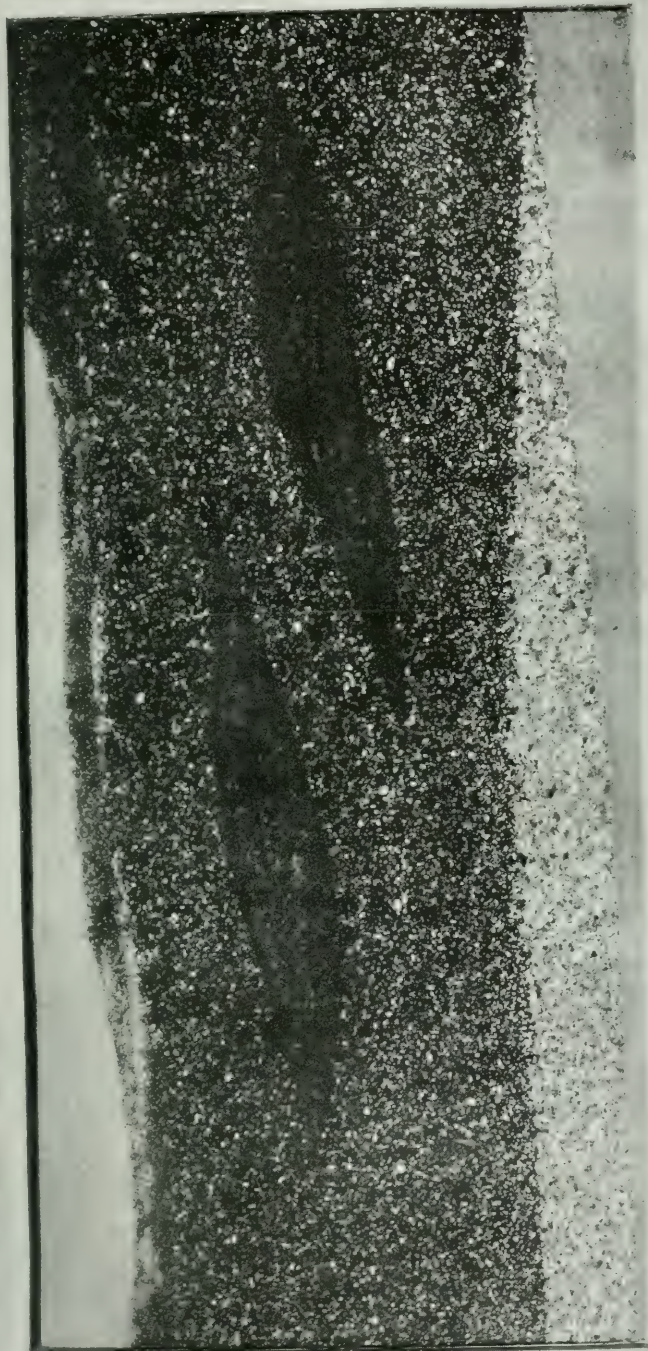


FIGURE 16.—Plot showing effect of water on oil production of a well.

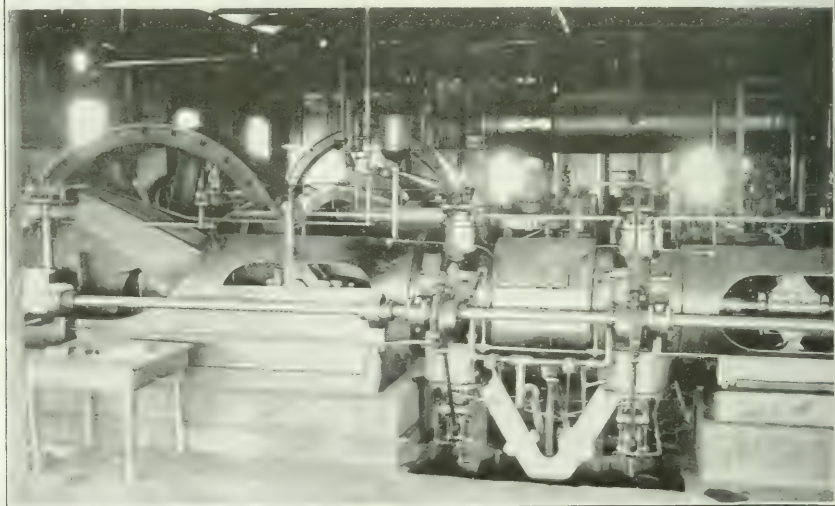
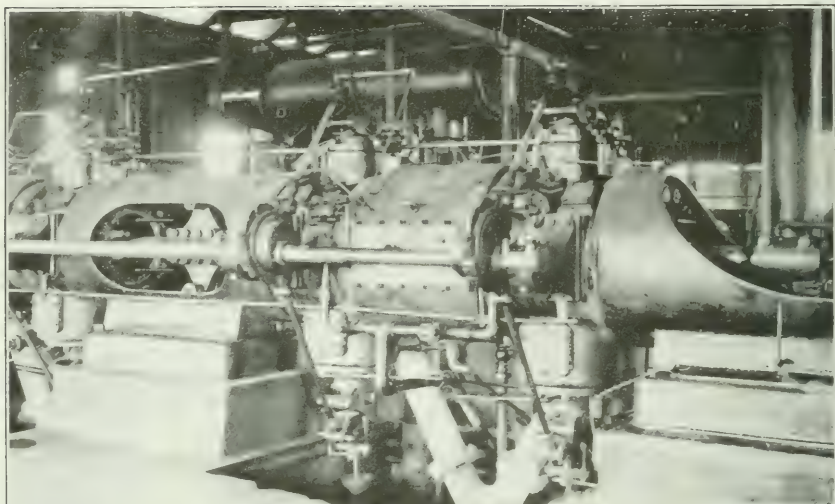
with air it could be cleaned out to the bottom with little difficulty. At times the fluid contained over 50 per cent sand. * * *

It has been found that by measuring the air used in blowing a well and by gaging the fluid produced in a certain length of time, that by volume 10 to 50 times as much air is required as fluid raised. This figure varies inversely with



CONTAINER AFTER SAND WAS FLUSHED WITH WATER.

The fluid flowed rapidly through the coarse sand, that is along the lines of least resistance, leaving oil behind in the fine tight sand. (See text, pp. 70-72.)



TWO VIEWS OF PART OF THE AIR COMPRESSOR EQUIPMENT OPERATED AT ONE TIME BY THE PEERLESS OIL CO., NOW THE ARIZONA OIL CO.

View shows extensive apparatus necessary to operate from 18 to 20 wells in this manner.

(After E. W. Waggy.)

the submergence, so that the extreme figure is probably often reached when pumping heavy viscous oils with submergence of only 30 per cent or less. * * *

Highest efficiency conditions are not maintained, because in most conditions the object of the lift is to keep the water level down, in order to prevent it from flooding the oil sands. Therefore the percentage of submergence is generally as low as can be obtained. * * *

The over-all efficiency of such a system varies from 5 per cent to 40 per cent and is calculated as the ratio of the water lifted from the fluid level in the well to the surface to the initial horsepower furnished the compressor. Except in cases where small units have been used for one well, it is difficult to obtain these figures. * * *

One of the main reasons for installing a system of this kind was for the purpose of trying to exhaust the water that was coming into the wells. However, instead of the water supply being exhausted, it increased in volume to such an extent that the air-compressor units had to be increased from one to three in some cases. (See Pl. XVIII.) * * *

Production figures of oil companies have shown that this one of the most inefficient and costly methods of producing oil. Even after equipment costing from \$7,000 to \$62,000 had been installed, on operating it for a comparatively short time it had to be abandoned in favor of remedial measures carried on under another heavy expense. The last remedy was repair work on individual wells. * * * The proper method to have pursued would have been to make such repair work before attempting the installation of what ultimately turned out to be useless machinery.

The intense agitation and intermingling of the air with the oil will cause losses of the lighter products of the oil when the air is finally liberated, thus reducing the gravity of the oil.

Another disadvantage that is not ordinarily taken into account when using compressed air is the formation of emulsions which are hard to treat for extracting all the water. The violent agitation caused by the compressed air forms a mixture of water and oil, in which the water is present in a very finely divided form. Often resort must be had to special methods to break up this emulsion. This leads to more expense for the installation of suitable equipment.

Conclusions.—It has been pointed out that the initial costs of compressor plants are high and their efficiencies are quite low. It has also been demonstrated that the water can not be exhausted, but tends to increase, and the oil production decreases. The production of oil may increase for a while when air is first used, but this is on account of the larger volume of fluid being raised to the surface. After a short time the peak will be reached and the oil production will decline as the water increases. The life of such plants has been comparatively short. * * * In nearly all cases the flow of water increased so fast that extra units had to be installed from time to time until production costs became prohibitive. This was one of the main reasons for starting repair work to try to overcome water troubles. It would have been a great deal better for the field to have considered such measures before installing this expensive machinery. This consideration is in general to be recommended in all oil fields where water troubles are prevalent. * * *

Concrete examples of repair work on wells which permitted abandonment of air compressors have been discussed by the California State Mining Bureau.²¹

²¹ Second Annual Report of the State Oil and Gas Supervisor of California for 1915-16: Calif. State Mining Bureau. Bull. 82, 1918. pp. 254-260.

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DIFFERENT WATERS IN A WELL.

CONTENTS OF A SAND.

The operator should consider the contents of a sand as an unknown quantity unless the sand has been tested, preferably by bailing or pumping, or unless there is positive evidence that the sand contains oil, gas, or water. It is well to remember that in a drilling well filled to the top with fluid, as is done in California or where rotary tools are used, this fluid will likely hold back any showings of oil, gas, or water. Unless the water is artesian or has some particular characteristic, as hydrogen sulphide odor, a water sand may be passed through unnoticed by the driller. This is particularly true of a rotary drilled well where the fluid contains much mud, as its specific gravity is heavier than the thin mud fluid or clean water used in a well drilled with standard tools.

The writer's experience with some "sulphur-water" wells which were drilled with cable tools is cited here to show the difficulty of determining whether a sand contains water when the hole is full of fluid. After testing and analyzing the waters of several wells, the sulphur-water sand was definitely located in a certain area. One well was known to be deep enough to reach the sulphur-water sand, but the fluid taken from the bailer when run to bottom showed no evidence of "sulphur." As the water in the hole was that previously run in from the hose, and the head of water in the hole was greater than that in the sand, no sulphur water came in. In fact, the sand slowly took rather than yielded water. The well was then bailed vig-

orously, after which the fluid smelled of hydrogen sulphide and gave a positive "silver-coin" test, which was evidence that the well had reached the sulphur-water sand. This test is one commonly used in oil-field practice to determine whether the water contains "sulphur" (hydrogen sulphide). A bright silver coin is placed in the water to be tested. If the coin turns dark, the test is positive, but if no film forms on the coin, it is considered that hydrogen sulphide is not present in appreciable amounts.

DIFFERENT POSSIBLE WATERS IN A WELL.

Waters occurring in sands above the producing oil horizons are generally known as top or upper waters, and those below the producing oil horizons as bottom or lower waters. Where there are several producing sands, water occurring between the producing zones is usually referred to as intermediate water. In addition to the different waters just mentioned, namely, top, bottom, and middle waters, it is also necessary to consider in the succeeding pages edge water, water in the base of an oil sand, and a lenticular sand carrying water.

A discussion of the academic viewpoint follows, wherein precise distinctions are made in the field between top water, bottom water, intermediate water, edge water, and water in the base of an oil sand. The operator does not always make these academic distinctions. The practical terminology is discussed on pages 87 and 88.

TOP WATER.³²

The top or upper waters are those lying in sands or other porous formations above the producing oil horizon. (See fig. 17, water sands A and A-1, and fig. 22 (p. 87) sand A.) In some fields the operator may term top water that water overlying the main productive zone, even though there are some shallow light producing sands higher up. Strictly speaking, such a water should be called middle or intermediate water.

In many fields the shallow, potable, top waters are of value for domestic use, also they often furnish water to the hole while drilling is in progress. When the drill reaches the producing oil horizons it is highly important that top waters be permanently excluded from the hole. Of the various methods used for this purpose undoubtedly the cementing method³³ is the most satisfactory, although a great number of satisfactory water shut-offs have been made by mudding³⁴

³² See also pp. 126, 136 and 137, 140 to 143.

³³ See Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163, Bureau of Mines, 1918, 122 pp.

³⁴ See Lewis, J. O., and McMurray, W. F., The use of mud-laden fluid in oil and gas wells: Bull. 134, Bureau of Mines, 1916, 86 pp.

or by landing the pipe on a good seat of tough shale, sticky clay, hard shell, or limestone for a formation shut-off. Where the top waters have a considerable hydrostatic head the cementing method should be used. Before the pipe is landed several feet of small hole should be drilled ahead in order to insure a tight fit for the casing shoe.

Samples of water from drilling wells should be collected for analyses.

In a finished well the top waters may have access to the underlying oil sand through a defective water shut-off, but water may also enter a properly drilled well from a neighboring well where the upper waters have access to the oil sand and are working through to other wells. Bottom or other water may likewise come from a neighboring well.

In the well itself top water may have access to the hole by: (1) The shut-off being too high; (2) the water leaking around the shoe

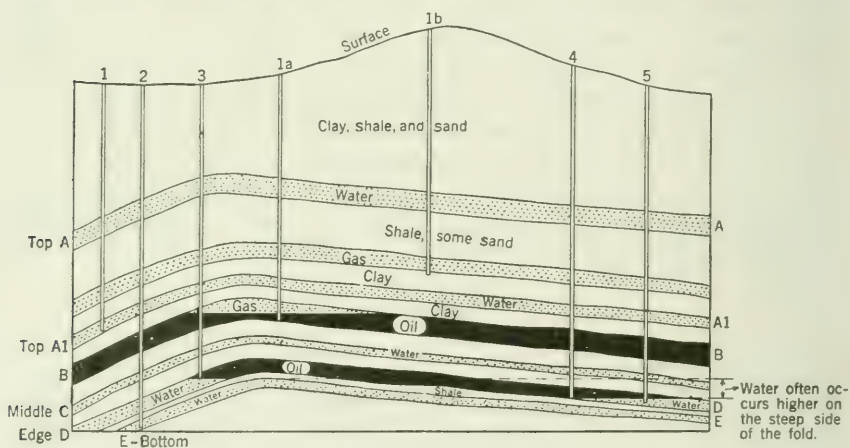


FIGURE 17.—Hypothetical sketch to show different water sands. Wells 1, 1a, and 1b were drilled to the same depth, but only 1a got oil.

of the water string; (3) poor coupling connections due to cross threading or the pipe not being sufficiently screwed together; (4) collapsed casing; (5) a split in the casing, the pipe worn through by the drilling line, or corrosion of the casing by strong corrosive waters in the sands.

An interesting example of a water string being cemented too high is shown in figure 18. It was not understood why this well did not make water, as the correlation indicated that the shut-off was too high. During a period of reclaiming pipe the oil string was cut at 1,851 feet and pulled, as shown by the center sketch of figure 18. Following this, the well showed an appreciable amount of water, and for some time the source of this water was not known. An analysis of the water and a study of adjacent wells indicated that it was com-

ing from a water sand situated just below the casing shoe, at 1,865 feet. A packer was then placed on the tubing between the liner and the tubing, as in the right-hand sketch of figure 18. This stopped the well making water.

The conclusions reached were that, prior to cutting the oil string, the water did not have sufficient head to rise to the surface between the oil string and water string, and could not move downward because of the "cavings" that had fallen in between the side of the hole and the blank pipe. Only the bottom 190 feet of the oil string

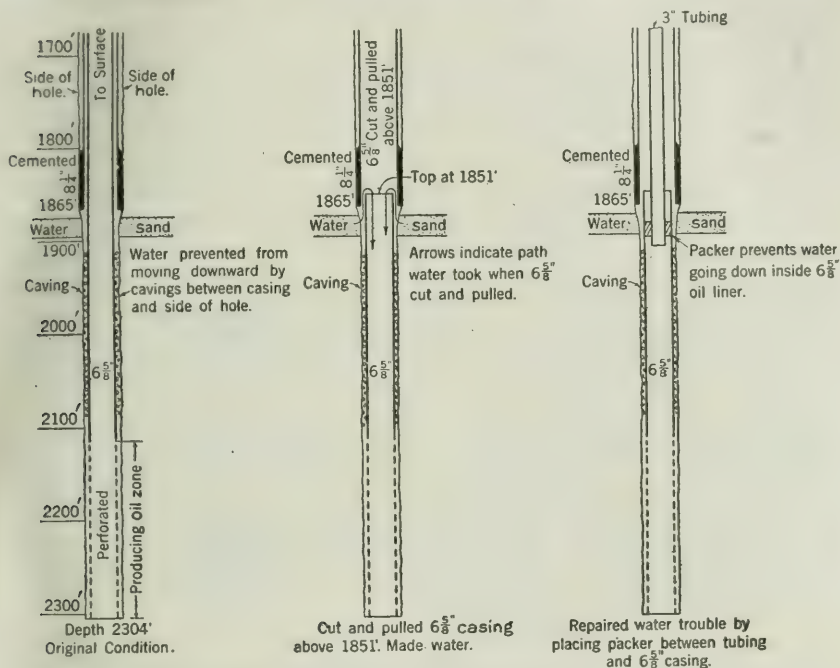


FIGURE 18.—Sketch showing "cavings" keeping water out of oil sand. (See text.)

was perforated. After insertion of the packer the water could not move down inside of the oil liner because of the packer placed between the tubing and the liner. This work emphasized the necessity of knowing the depths of the perforations and location of the water sands, also the practical application of water analyses.

BOTTOM WATER.³⁵

Bottom water, as the name implies, is that water occurring below the producing oil horizon. (See fig. 17, p. 80, sand E, and fig. 22, p. 87, sand D.) The writer has distinguished between water in the

³⁵ See also pages 127, 137, and 143 and 144.

base of an oil sand and the true bottom water that occurs in a separate sand from the oil, usually separated by a "break" of shale or other impervious formation.

Bottom water has forced itself into prominence by the serious damage and trouble caused in many fields. To avoid such trouble, it is important to learn the exact distance between the top of the water sand and the base of the oil zone, so that the operator can avoid drilling too deeply. Unfortunately, a few wells must be drilled into bottom water before it can be accurately located. After these wells have been plugged and the water shut off, future trouble of this kind should be avoided.

When a well is brought in and apparently making oil and water from the same sand, the operator should not be hasty in concluding that they occur in the same sand. Such an occurrence is entirely possible, but it may be that a small break or parting separates the oil sand from the water sand. When the parting is thin, great skill and care are required to avoid drilling into or to shut off the bottom water. An impervious break of 1 foot will serve as a barrier to separate the oil and water. Unless this parting is a very hard limestone, a very tough shale, or some such formation that will attract the attention of the driller by certain drilling characteristics, it may be passed by without notice. This is particularly true if a well is "drilled in" to the oil sand by a rotary.

Before deciding that the oil and water occur together a careful investigation with proper tests should be made to determine whether there is a break between the two. If such a parting exists, there is much more hope for repairing the well; but if the water and oil are associated together, the repairing of the well is a very difficult matter.

INTERMEDIATE AND MIDDLE WATER.³⁶

The water occurring in a sand located between two or more productive oil horizons is referred to as intermediate water. If there are only two productive sands, the term "middle water" is often applied to the water occurring between them. (See sand C, fig. 17, p. 80, and sand B, fig. 22, p. 87.) A territory in which intermediate or middle water has a large hydrostatic head presents a complex and often expensive developing problem (see pp. 149 to 156), because it is not safe practice to produce from the upper and lower zones in the same well. In fact, where the water has a large head it precludes the oil sands and water sands being exposed in the same well, as the head of water will prevent the oil coming in.

Packers have been used in an effort to keep the water in its own sand (see p. 145), but in general they are not successful.

³⁶ See also pages 127, 137, 138, 144, and 145.

A method for developing an area with a middle water of large head is brought out in figure 19. To cement the well at 2,000 feet and produce from both oil sands A and B would not be possible, because the water W would hold back the oil and flood A and B. In developing such a property with conditions as shown in the figure, the operator can land a water string at about 2,000 feet, deepen the well to 2,055 feet, and produce from oil sand A. When this sand is exhausted he could pull the oil string, land and cement a string of casing at about 2,130 feet, which is between water sand W and

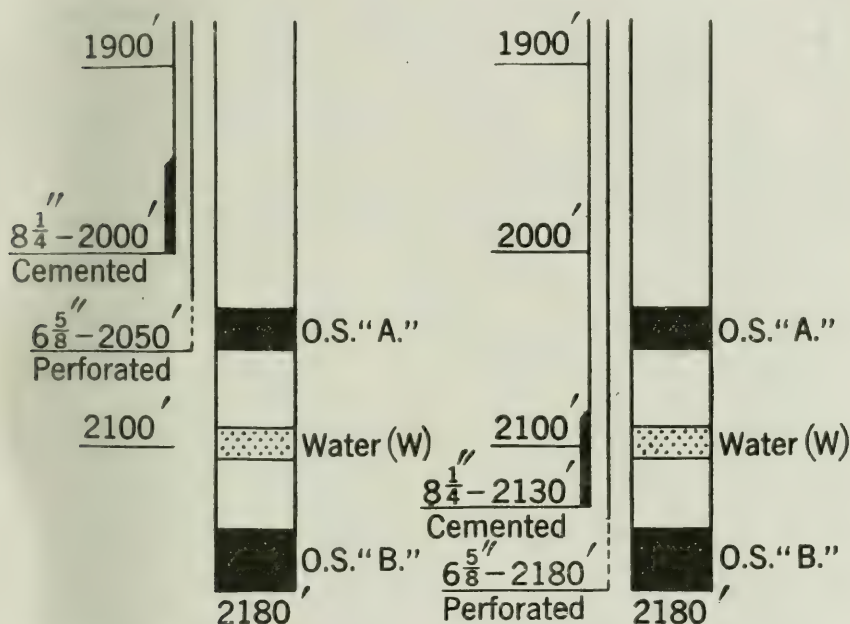


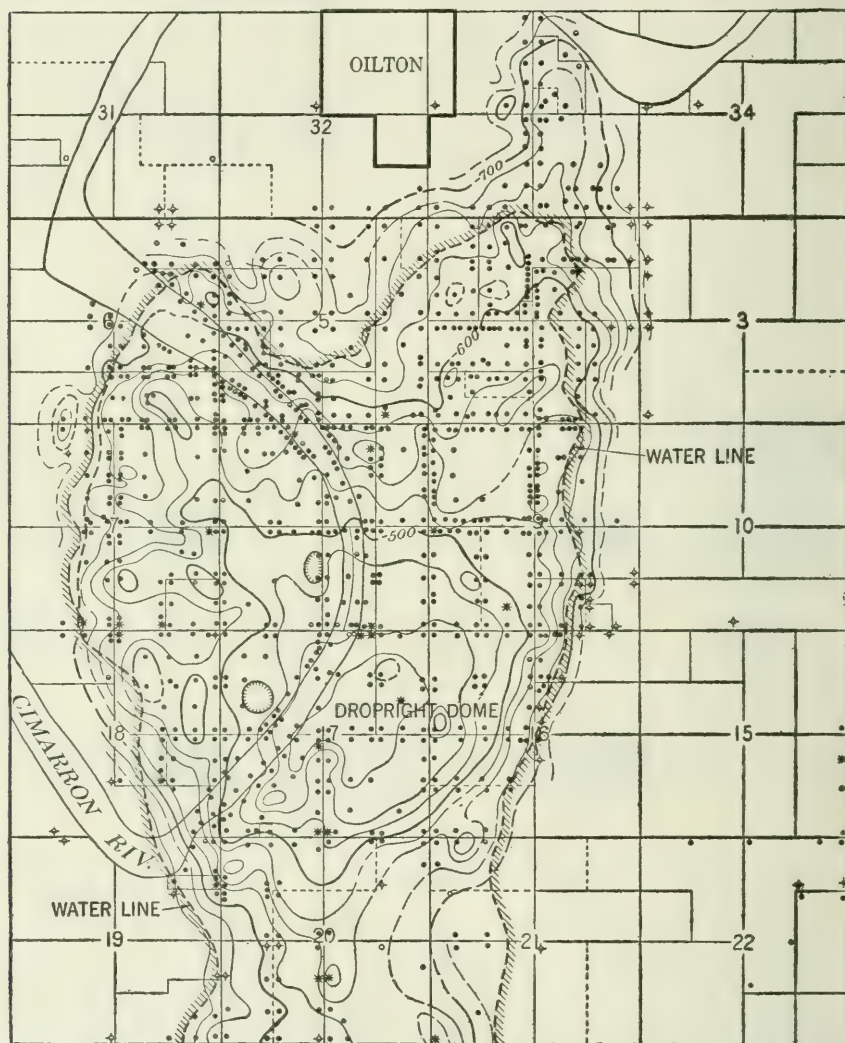
FIGURE 19.—Sketch to illustrate additional cost of producing where there is a middle water.

oil sand B, and then produce from sand B. This would take the least number of wells.

If it is desired to obtain all of the oil as soon as possible, two series of wells may be drilled, one to produce oil from sand A and the other from sand B. In the wells producing from oil sand B there must be placed behind the pipe sufficient cement to extend above oil sand A in order to protect the latter from the underlying water. Also, a heavy batch of mud-laden fluid may be used behind the 8 1/4-inch casing at 2,130 feet to protect sand A. This may be in addition to the cement, or without the cement, provided great care is taken to mud off oil sand A and water sand W.

EDGE WATER.³⁷

Edge water is the water occurring in the down-slope part of an oil or gas-bearing stratum. (See sand D, fig. 17, and sand C, fig.



LEGEND

- — Rig
- — Drilling well
- ◇ — Dry hole
- — Oil well
- * — Gas well
- ✦ — Abandoned oil well
- ✧ — Abandoned gas well

FIGURE 20.—Map of area in vicinity of Dropright dome, Cushing oil field, Oklahoma, showing edge-water line cutting across structure contour of Layton sand. After C. H. Beal. (Beal, C. H., Geological structure in the Cushing oil and gas field, Oklahoma: Bull. 658, U. S. Geol. Survey, 1917. 64 pp.)

³⁷ See also pages 127, 138, and 145 and 146.

22.) The line of contact between the oil or gas and the water in steeply dipping strata is usually referred to as the "edge-water line." If the dip is steep the plane of contact between the water and oil will be narrow, but if the dip is almost flat the plane of contact will be broad. Thus, wells drilled down slope from the edge-water line will encounter water in the same stratum in which oil or gas is found up slope, provided the stratum is of fairly uniform porosity.

The anticlinal theory for the accumulation of oil and gas, which has been generally accepted, depends on the differences in the specific gravity of gas, oil, and water. Water, being the heaviest of the three fluids, is at the base of the collecting stratum: as the oil or gas up slope is withdrawn it is replaced by water. The rate of approach of the edge water largely depends on the rate of withdrawal of the oil and gas, the porosity of the sand, the hydrostatic pressure, and the temperature of the oil.

Figure 17 (p. 80) indicates that edge water occurs higher on the steep side of the fold. This is often true.

The edge-water line more or less parallels the underground contours, but in many places it cuts across contours and occurs up slope. By following the dashed line representing the edge-water line, in figure 21, the reader will see that it crosses the contours after no particular fashion. It crosses the 550-foot contour in the northeast quarter of section 4; in section 18 it runs well up on the dome. Attention is called to the fact that this field has several oil sands and that the producing wells shown outside the edge-water line may be drawing production from other than the edge-water sand.

The edge-water line may also cut across contours in localities of excessive development. This is shown in figure 21. The encroachment line swings up irregularly from the original edge-water line, on account of the great quantity of oil withdrawn by the wells along the section line. As a result, water appears in well B, but well A, which was drilled much later, has no water, even though farther down the slope. Not much oil has been withdrawn in the direction of A, owing to its being a comparatively new well. The edge water

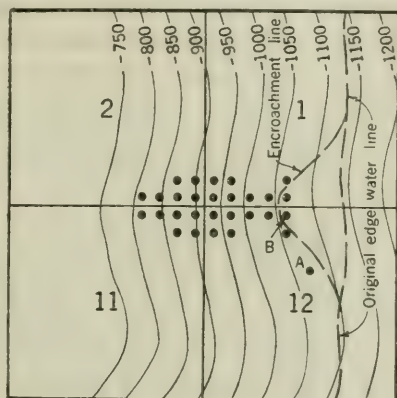


FIGURE 21.—Sketch to show edge-water line cutting across structure contours due to excessive development locally.

moved up slope to replace the oil and gas withdrawn along a narrow belt where an excessive number of wells have been drilled near the section lines. Under such a condition the edge water cuts across underground contours, forming a narrow salient which extends toward the point of greatest development from the original location of the edge-water line. A well inside this salient will, of course, produce water rather than oil.

In some of the older wells flow channels for withdrawal of the oil and gas may be established in such a way that certain wells down slope in the heart of the water area may be by-passed by the water. The channeling may be due, perhaps, to difference in porosity, cementation of sands, or to filling in of the sand pores with mud of comminuted shale surrounding these wells. The water naturally works up through the flow channels already established, hence wells up the slope may show water while a few wells down the slope will be free from water. In replacing the withdrawn oil and gas the water is certain to entrap large quantities. (See plates XV to XVII and discussion on pp. 70 to 72.) When edge water is present sooner or later production of oil will suffer.

WATER IN THE BASE OF AN OIL SAND.³⁸

Water may occur in the base of an oil sand, but before drawing such a conclusion it is advisable to consider carefully whether there may not be a thin impervious stratum between the oil and water. (See p. 146.)

In a flat-dipping bed containing both oil and water the plane of contact between the oil and water will be extensive, provided the porosity of the sand is more or less uniform, but as the dip steepens the plane will become smaller until in steeply tilted beds it is referred to as an edge-water line.

When water occurs in the base of the oil sand the operator is certain to experience much difficulty in future operations. Every effort should be made to delay the advance of the water where possible, so that the maximum amount of oil may be recovered.

LENTICULAR WATER SAND.

Formations are often lenticular and pinch out within a short distance. (See discussion on lenticularity and correlation, pp. 42 to 44.) If such a lenticular sand carries water, it is termed top, bottom, or middle water, according to its location with respect to the oil sands.

A lenticular sand containing water may completely pinch out between two impervious shale members, as sand B in figure 22. Under such conditions careful study and comparison of the different well logs is necessary in order to arrive at the exact conditions under-

³⁸ See also pp. 128, 138, 139, and 146 to 148.

ground. When marked lenticularity occurs the sand containing middle water B, as found in well 2, figure 21, may grade out and entirely different conditions exist at a corresponding stratigraphic depth in well 1. Well 1 encountered gas in a sand stratigraphically equivalent to water sand B, whereas water would be the thing to expect if the sand had been continuous. In such a case the operator might be misled into thinking this was an edge water below the gas zone.

One operator's experience is cited here to show the difficulties occasioned by a lenticular sand. A well was producing oil and no water. Later another well was drilled 600 feet distant and to the same stratigraphic horizon. It came in producing water with the oil. The second well caused much trouble, and tests were made for bottom water and top water. After a great deal of testing and detailed study, it was decided that the water sand in the second well

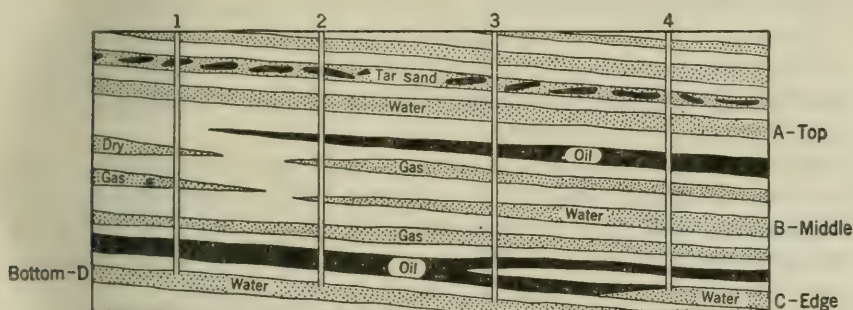


FIGURE 22.—Sketch showing lenticular sands.

pinched out before it reached the first well. When a lens of sand pinches out on all sides, then the hydrostatic head of the entrapped water is often low.

REGIONAL AND LOCAL TERMINOLOGY OF DIFFERENT WATERS.

As previously stated, the uses of the various terms, "top water," "bottom water," "intermediate water," etc., may be considered in two different ways: First, the academic point of view, in which broad distinctions are made over an entire field after sufficient development work has been done to show the whole structure and what is found in each sand at the various parts of the field; second, from a local point of view, in which only one small property is concerned.

Figure 17 (p. 80) gives examples of top, bottom, edge, and middle water, so named when the whole structure is considered. But suppose the first development had been at well 2, then the operator would have called the water in sand D bottom water. This terminology may have come into such common use in the field that by the time the technical man had worked out the true relations he

could not possibly change it. Similarly, as regards only local areas, a water may be called top water which is really a top edge water when the whole structure is considered. There may be middle water locally, but this would be termed "bottom water" in that part of the field where there was no production in the lower sands. Different occurrences of oil and water will give rise to local names for one water in the same field.

The second way of looking at the terminology is chiefly concerned with corrective measures on a particular well. To the operator, who is repairing the well, the important thing is whether water is coming from a sand overlying his producing oil sand and separated from it by an impervious material. He is not particularly interested in whether this water sand contains oil or gas in another part of the field. In the same way he is concerned with water below his oil sand, and it makes no difference to him whether his neighbor is producing oil from this sand which bears water on his property.

However, if water occurs in the same sand as his oil and it is encroaching, he is vitally interested. Edge-water conditions of a neighboring property should likewise interest him, because this water may encroach to his property.

Drawing fine distinctions in terminology between the various types of waters is often useless and confusing. What is wanted is some designation that will be understood by everybody. If the sand has been given a name, it will be proper to use the name to designate the water, as, for example, "Sand D, edge water."

In many places the water and oil may move so that the conditions found when a property is first opened up may change during its life. Therefore the operator should have the advice of a technical man based upon a study of surrounding conditions, so as to take into account any movement in the producing sand or the overlying or underlying sands.

CHEMICAL ANALYSES OF WATER.

Operators in many oil fields have recognized the importance of knowing the composition of the underground waters encountered, and they have often made profitable use of the results of water analyses in solving oil-field production problems. Many operators, nevertheless, look on water analyses with apparent indifference. Their skepticism may be due to the fact that the usual report of a chemical analysis of water has been a bald statement of the amounts of different substances or parts of substances contained in a given quantity of the water examined, telling nothing of their effect on a water and offering nothing to distinguish the items from one another, except their names.

Underground waters, like surface waters, are solutions of several inorganic salts and their qualities or characters depend on the chemical nature and proportional amounts of the substances present. For instance, every substance dissolved in a water imparts to the solution some definite quality peculiar to the dissolved substance. A solution of calcium sulphate is hard and saline, one of sodium sulphate is soft and saline, a solution of sodium carbonate is soft and alkaline, a solution containing both sodium sulphate and sodium carbonate is soft, saline, and alkaline.

By simple inspection anyone can see that calcium causes hardness in waters, sodium does not; sulphates cause salinity, and carbonates indicate alkalinity. The properties or qualities of solutions consisting of mixtures of salts dissolved in water can be determined as accurately as the constituents which confer these properties on waters can be determined. Salinity and alkalinity are fundamental properties of natural waters, therefore, if the chemist's report of an analysis of a water is intended to indicate the kind of water analyzed, his results should be stated in a form that shows the relative values of these properties.

A system of chemical hydrology based on the chemical nature and proportional amounts of the substances dissolved in natural waters has been established by Palmer.³⁹ In this system water analyses are interpreted in terms of the properties conferred on natural waters by the inorganic substances dissolved in them. His publications show clearly that the results of water analyses may now be used successfully in scientific investigations and may also be applied profitably to the solution of industrial problems. In a chemical survey of river waters of the United States, Palmer shows the close relation of the properties of waters to geologic formations; he traces the changes in the properties of river waters caused by changes in type of rock material, and discovers the manner in which the water of an inland sea, like Lake Erie, is modified by the river waters discharging into it waste brines coming from the numerous oil wells of northern Ohio.

By means of the reaction properties of western stream waters, Van Winkle has made valuable contributions to geology. For instance, the formations underlying the southern part of Puget Sound were formerly supposed to be sedimentary rocks. Van Winkle⁴⁰ observed the water of Wood Creek to be primary alkaline, indicating that the prevailing rock is of igneous origin. The evidence of his water analyses indicates that the glacial drift in the basin of Wood Creek was derived from the igneous rocks of the Cascade Range and not from the sedimentary rocks of the valley floor.

³⁹ Palmer, Chase, *The geochemical interpretation of water analysis*: Bulletin 479, U. S. Geol. Survey, 1911, 31 pp.

⁴⁰ Van Winkle, W., *Quality of the surface waters of Washington*: Water Supply Paper 339, U. S. Geol. Survey, 1914, pp. 39-40.

The rocks of northeastern Oregon were formerly supposed to be volcanic. The properties of the water of Wallowa River indicate that this opinion is wrong. Van Winkle⁴¹ found the water to be secondary saline. As secondary salinity is characteristic of sedimentary formations, he was led to suspect that in the upper part of the basin calcareous rocks would be found. Special investigations of that region disclosed the existence of several faults and between them large deposits of sedimentary rocks resting on diorite.

By comparing the chemical properties of waters from interior and border wells of the Ozark Uplift Siebenthal⁴² was led to discover the kind of water from which the enormously rich deposits of lead and zinc ores were formed, and thus afforded a solution to a most difficult problem in ore deposition.

These examples show very clearly that by interpreting water analyses, according to the chemical properties of waters, geologists have already obtained important and definite results. They suggest also that the new interpretation of water analyses can help the petroleum engineer to outline a better defense against the water menace.

INVESTIGATION IN COALINGA OIL FIELD, CALIFORNIA.

Convinced that knowledge of the chemical qualities of oil-field waters would help to overcome difficulties caused by water in oil wells, the writer in 1915 made a preliminary survey of the waters in the East Side field, Coalinga, for the Shell Co., of California. The primary object of the investigation was to discover the sources of the various waters. In September, 1916, a report of the work was made to B. H. van der Linden, field manager of the Shell Co. The original report was based on analyses of 40 samples of water carefully chosen from wells belonging to the company and from a few neighboring wells. The cost of the original survey was about \$700, but this work has saved the company this amount of money many times over. In order to point out the advantages of such work, a short account of some of the findings of that report is here given.

INTERPRETATION OF ANALYSES.

The analytical results as reported by the analysts are not used to compare and classify the waters, but serve rather for obtaining chemical values such as are now used generally by hydrologists of the United States Geological Survey and by other progressive hydrologists.

⁴¹ Van Winkle, W., Quality of the surface waters of Oregon: Water Supply Paper 363, U. S. Geol. Survey, 1914, p. 65.

⁴² Siebenthal, C. E., Origin of the zinc and lead deposits of the Joplin region: Bull. 606, U. S. Geological Survey, 1915, p. 155-156.

The chemical interpretation of a water analysis is based directly on the reaction capacities, or functional weights, of the constituents as distinguished from the gravity weights reported by the analyst. It describes the water as a solution having a few special properties of which the general properties, salinity and alkalinity, are composed. This interpretation has been adopted for the following reasons:

1. The fundamental character of a water depends on the relative proportions of salinity and alkalinity.
2. A natural classification of water is thus obtained.
3. Different waters may be accurately and rapidly compared.
4. Results are expressed concisely.

PROPERTIES OF SOLUTIONS.

The properties of a solution are the assembled properties of all the active parts of the substances contained in the solution; hence the properties of a water can be determined by measuring its action on other substances whose natures are known, or they may be derived by calculation from the statement of a water analysis. The cause of salinity and alkalinity is concisely stated by Palmer,⁴³ as follows:

All the radicals of the alkalis and alkaline earths tend to form alkaline solutions, but only the strong acid radicals (sulphate, chloride, nitrate) can overcome this tendency and render an alkaline solution neutral or saline. The sum of the reacting values of the strong acid radicals is therefore a measure of the salinity (saltiness) of a natural water which is a solution of salts of strong and weak acids. The sum of the reacting values of the metallic radicals in excess of the values of the strong acids is a measure of the alkalinity of a water.

Palmer's interpretation of water analyses comprises two distinctly different expressions, namely, a "character formula" and a statement of the chemical quality of the solution. The character formula shows in detail the relative reaction capacities of all the radicals determined in a water, without regard to their effect on the solution. In this formula the values of the basic and acidic radicals are balanced. It is primarily a chemical formula for the mixture of dissolved salts; but it is also a character formula, because from it the chemical character or chemical quality of the solution may be derived.

The second expression is a statement of reaction properties conferred on the solution by all the radicals present in the water, according to their natural resemblances and differences, and the numerical relations of these reaction properties are derived di-

⁴³ Palmer, Chase, A deep well at Charleston, S. C.: Prof. Paper 90, U. S. Geol. Survey, 1914, p. 92.

rectly from the reaction capacities of the radicals as shown in the "character formula." Both of these expressions should be used to obtain a comprehensive knowledge of the chemical quality of a natural water.

RADICALS AND THEIR REACTING VALUES.

Many commercial chemists report an analysis of a water in grains of chemical compound per gallon. Each compound can be readily divided into radicals by considering their proportional atomic weights. Thus, 7.34 grains per gallon of sodium sulphide (Na_2S), gives

$$\begin{aligned}\text{Atomic weight of Na} &= 23; \text{ S} = 32. \\ 46 \div 78 \times 7.34 &= 4.32 \text{ grains per gallon of Na.} \\ 7.34 - 4.32 &= 3.02 \text{ grains per gallon of S.}\end{aligned}$$

Factors for calculating the amount of the base radical found in oil-field waters are as follows. The amount of acid radical is found by subtraction as above:

Compound.	Base Factor. radical.
Sodium sulphate (Na_2SO_4)	$\times 0.324 = \text{Na}$
Sodium chloride (NaCl)	$\times 0.393 = \text{Na}$
Sodium carbonate (Na_2CO_3)	$\times 0.434 = \text{Na}$
Sodium sulphide (Na_2S)	$\times 0.589 = \text{Na}$
Calcium sulphate (CaSO_4)	$\times 0.294 = \text{Ca}$
Calcium chloride (CaCl_2)	$\times 0.361 = \text{Ca}$
Calcium carbonate (CaCO_3)	$\times 0.400 = \text{Ca}$
Magnesium sulphate (MgSO_4)	$\times 0.202 = \text{Mg}$
Magnesium chloride (MgCl_2)	$\times 0.255 = \text{Mg}$
Magnesium carbonate (MgCO_3)	$\times 0.288 = \text{Mg}$

The product of the number of grains (per U. S. gallon) of each radical multiplied by 17.12 gives the parts per million in solution of that radical. However, if an analysis is reported in grains per gallon, it is not necessary to change the values in the computation to parts per million. This is shown in Form 3 (p. 105) where the reaction coefficients are multiplied directly by the grains per gallon of each radical.

Natural waters usually contain the following radicals:

- Sodium (Na) and potassium (K)—Alkalies (positive).
- Calcium (Ca) and magnesium (Mg)—Alkaline earths (positive).
- Sulphate (SO_4) and chloride (Cl)—Strong acids (negative).
- Carbonate (CO_3) and sulphide (S)—Weak acids (negative).

Upon the proportional reaction capacities of these four groups of radicals depend the properties that distinguish waters from one another. The reaction capacity of a radical is the quotient of the actual weight of that radical divided by its equivalent combining weight. This quotient is the reacting value of that amount of the radical. Instead of laboriously dividing these weights, it is more convenient to

multiply the weights of the radicals by the reciprocals of their equivalent combining weights, called "reaction coefficients." The reaction coefficient of a radical, then, is the ratio of one part of that radical to the reaction capacity of eight parts of oxygen (8 equals the equivalent weight of oxygen).

For sodium, which has an atomic weight of 23 and an equivalent coefficient equal to $1/23$, the reaction coefficient is 0.0435.

The reaction coefficients of the active radicals usually present in waters are:

Reaction coefficients of active radicals.

Positive radicals.	Reaction coefficients.	Negative radicals.	Reaction coefficients.
Sodium (Na).....	0.0435	Sulphate (SO ₄).....	0.0208
Potassium (K).....	.0256	Chloride (Cl).....	.0282
Calcium (Ca).....	.0499	Nitrate (NO ₃).....	.0161
Magnesium (Mg).....	.0822	Carbonate (CO ₃).....	.0333
		Sulphide (S).....	.0624

CONVERSION OF PHYSICAL WEIGHTS INTO REACTING VALUES.⁴⁴

An analysis of water from the Shell Co.'s well No. 16, sec. 26, T. 19 S., R. 15 E., in the Coalinga field, California, follows:

Results of analysis of water from well 16, showing reacting values.

[Smith, Emery & Co., analysts.]

Radicle.	Parts per million.	Reaction coefficient.	Reacting values (equivalent to milligrams of hydrogen).
Sodium (Na).....	1003.2	× 0.0435	= 43.64
Calcium (Ca).....	17.3	× .0499	= .86
Magnesium (Mg).....	8.7	× .0822	= .71
			45.21
Sulphate (SO ₄).....	230.4	× .0208	= 4.79
Chloride (Cl).....	54.5	× .0282	= 1.54
Carbonate (CO ₃).....	1067.0	× .0333	= 35.53
Sulphur (S).....	51.7	× .0624	= 3.23
			45.09
Total value.....			90.30

The fourth column is a translation of the actual results reported by the analysts. Like the analysts' statement, the expression of reacting values takes into account the actual quantities of the radicals, but, unlike that statement, it discloses a balance between the positive and negative radicals, and thus forms a basis for a logical interpretation of the quality of the water analyzed. As actual values vary with the concentration, in order to compare waters of different concentrations all the values must be referred to the same degree of concentration.

⁴⁴ See p. 105 and Form 3.

This is done by omitting the concentration factor altogether, and by expressing the reacting values in percentages, thus:

Results of analysis of water from well 16, with reacting values expressed as percentages.

Radical.	Reacting values.	Character formula.
		<i>Per cent.</i>
Sodium.....	43.64+90.3=	48.3
Calcium.....	.86+90.3=	.9
Magnesium.....	.71+90.3=	.8
		50
Sulphate.....	4.79+90.3=	5.3
Chloride.....	1.54+90.3=	1.7
Carbonate.....	35.53+90.3=	39.4
Sulphide.....	3.23+90.3=	3.6
		50

The statement of the analysis in percentage reacting values dispenses with all arbitrary units of physical measurement and retains only the reacting ratios of the radicals which together constitute a chemical system of dissolved salts. The statement is strictly a chemical formula; it is based on no hypothesis and no theory, but rests solely on the fundamental chemical law of equivalent combining weights. This formula is capable of wide application. It discloses not only the relative reaction capacities of all the radicals determined in a water, but shows at a glance very slight differences in the values of the radicals of different waters.

DERIVATION OF SPECIAL PROPERTIES.

The alkalis, sodium and potassium, are called primary bases; the alkaline earths, calcium and magnesium, are called secondary bases. The strong acids in connection with an equal value of the alkalis, or primary bases, induces the property, primary salinity; in connection with the alkaline earths they produce secondary salinity. Primary and secondary alkalinity are measured, respectively, by the excess of the alkalis or alkaline-earth bases over the values of the strong acids.

From the character formula already given of the water from well No. 16, the reaction properties of the solution are derived as follows:

Reaction properties of radicals in water from well No. 16.

		Properties of reaction.
Strong acids (5.3+1.7).....=	7.00	
Alkalies	7.00	
		Primary salinity..... 14.00
Alkaline earths (0.8+0.9)	1.70	
Weak acids.....=	1.70	
		Secondary alkalinity..... 3.40
Alkalies (48.30-7.00).....=	41.30	
Weak acids (39.40+3.60-1.70).....=	41.30	
		Primary alkalinity..... 82.60
		100.00

In interpreting water analyses it is often desirable to compare the values of different radicals in the character formula itself. For example, in studying the waters of the Coalinga field, comparison of the relative values of the chlorides and sulphates, in particular, has thrown additional light on the relation of a water to its surroundings. Thus, the sample from well 16 had a sulphate salinity of 5.3 and a chlorine salinity of 1.7, or the sulphate salinity was 76 per cent and the chloride salinity was 24 per cent of the total salinity caused by the strong acids. These values alone strongly suggest that the water is a solution caused by a mixture of a shallow water with another water of deep-seated origin.

GRADATIONS OF EAST SIDE COALINGA WATERS.

With respect to their stratigraphic position, the waters within the area of this survey may be designated as top, bottom, and intermediate waters.

TOP WATERS.

The top or upper waters are either above the Big Blue shale or 200 to 300 feet below the top of the Big Blue. In these waters the values of the alkalies and of the sulphates generally predominate, resulting in high primary salinity and high sulphate salinity.

Analyses of two waters known to be top waters showed the following properties:

Properties of two top waters, east side, Coalinga field.

	Shell Co. well 16-14.	Record Co. well 5.
Reaction properties:		
Primary salinity.....	85	82
Secondary salinity.....	7	0
Primary alkalinity.....	0	12
Secondary alkalinity.....	8	6
Subordinate properties:		
Chloride salinity.....	5	5
Sulphate salinity.....	95	95

The top water in Shell Co. well 16-14 comes from a bed about 250 feet below the top of the Big Blue shale and that in Record Co. well 5 is from a bed above the Big Blue.

BOTTOM WATERS.

The bottom waters are those coming from sands in the oil zone and seem to emanate 600 feet or more below the top of the Big Blue. A representative sample of bottom water obtained from Shell Co. well 16-14 had the following properties: Primary salinity, 10; primary

alkalinity, 78; secondary alkalinity, 12; chloride salinity, 100; sulphate salinity, none.

The source of the water is 728 to 840 feet below the top of the Big Blue. The sulphates in the water are completely reduced. It is characterized by high alkalinity, low primary salinity, and low sulphate salinity. Here the sulphate salinity is reduced to zero.

INTERMEDIATE WATERS.

Between the lower and bottom waters many so-called intermediate waters are found. Some of them tend toward upper waters and others tend toward lower waters as regards the distribution of their properties. The water in Shell Co. well No. 7-10 has properties characteristic of intermediate water as shown by the following analysis: Primary salinity, 30; primary alkalinity, 49; secondary alkalinity, 21; chloride salinity, 31; sulphate salinity, 69.

This water is 636 to 720 feet below the top of the Big Blue. Such a water may be due to a mixture of top and bottom waters or may be caused by partial reduction of the waters which come in contact with the oil.

In general, the range in properties of the waters of the East Side Coalinga field is probably as follows: The top waters have high primary salinity (75-100) and high sulphate salinity (90-100). The bottom waters have low primary salinity (0-15) and low sulphate salinity (0-10). The intermediate waters have properties whose values are intermediate between those of upper and lower waters. Their properties are caused by the effect of the oil on lower waters with consequent reduction of sulphates, increase in carbonates, and lowering of salinity. The upper waters are not in contact with the oil, so that the sulphates are not reduced; hence these waters have a high salinity.

PERSISTENCE OF PROPERTIES OF OIL-FIELD WATERS.

Unless the chemical proportions of the inorganic constituents, and consequently of the reaction properties, of an oil-field water are permanent features of the solution, the application of the results of a water analysis is limited to the water at the time it was sampled for analysis. In order to learn whether the character of a deep-seated water is transitory and subject to change, two samples of the waters from the same bailer were sent several weeks apart to a chemist for analysis. The chemist did not know that both samples were from the same source.

The reports of the two analyses, transposed into reaction values and terms, are as follows:

Interpretation of a water analysis.

	First sample.	Second sample.
Reaction values, in percentages:		
Sodium.....	43.1	48.5
Calcium.....	.3	.9
Magnesium.....	.6	.6
Sulphate.....	2.7	2.3
Chloride.....	16.7	16.9
Carbonate.....	30.6	30.8
Reaction properties:		
Primary salinity.....	38.8	38.4
Primary alkalinity.....	59.4	58.6
Secondary alkalinity.....	1.8	3.0

The close agreement of the two samples as regards all the factors of quality and the proportions of the reaction properties leaves little cause for doubting the persistence of the chemical character of the water under examination. This water, like nearly all the other waters considered in this chapter, is distinctly a primary alkaline water, and the constancy of its chemical character accords strictly with the permanence of the character of two deep-seated waters from artesian wells under Charleston, S. C. One of the wells is 1,260 feet deep and the other is over 2,000 feet deep. The waters in the two wells are from wholly different geologic horizons. For many years they have served the city of Charleston as a municipal water supply. From a careful investigation of these waters Palmer⁴⁵ has found them to be of the primary alkaline type. He has established the fact that the proportions of their chemical properties are wholly different and that they are from independent water courses, and he has shown that even after flowing for 35 years each water remains unchanged in respect to its chemical character and mineral content.

All the evidence thus far obtainable goes to show that the chemical properties of deep-seated primary alkaline waters are not subject to fickle changes, but are reliably constant.

USE OF CHEMICAL PROPERTIES OF A WELL WATER IN OIL-FIELD PRODUCTION PROBLEMS.

APPLICATION OF WATER ANALYSES IN COALINGA FIELD, CALIFORNIA.

To show the practical use of water analyses, a few concrete examples of their application to production problems on individual wells is given here.

⁴⁵ Palmer, Chase, A deep well at Charleston, South Carolina: Prof. Paper 90-H, U. S. Geol. Survey, 1914, p. 90-94.

Example 1.

The hole was open in a well, No. 8-10, 658 to 713 feet below the top of the Big Blue shale, and at this depth the well had a water sand making 45 barrels a day. Another well, No. 7-10, only 520 feet distant, had found a water sand at 720 feet, only 7 feet deeper stratigraphically than well 8-10. Well 7-10 was making 110 barrels of water a day. This fact led the company to suspect that the drill in well 8-10 would strike another sand only 7 feet deeper, and that the water string should be landed at least 720 feet below the marker.

The following table shows the properties deduced from analyses of waters in the two wells:

Comparison of chemical properties of well waters.

Well No.	Distance below top of Big Blue shale.	A. Special properties of reaction.				B. Subordinate properties.		
		Primary alkalin-ity.	Secondary alkalin-ity.	Primary salinity.	Total.	Sulphate salinity.	Chloride salinity.	Volume.
	<i>Feet.</i>							<i>Barrels per day.</i>
7-10.....	615-683	12	22	66	100	12	8	20
	(<i>a</i>)							
	636-720	49	21	39	100	69	31	110
	700-720	70	17	13	100	53	47	90
8-10.....	658-713	35	18	47	100	85	14	45

a The proper stratigraphic order of the water sand in well 8-10 is probably here, not at the bottom of the table.

This tabulation (see section A) shows clearly that the proportions of the special properties of the waters in well 7-10 change regularly with the depth of the well. For instance, the primary salinity—that is, salinity caused by sulphates and chlorides of the alkalies—decreases progressively with the depth of the well. On the other hand, the primary alkalinity advances steadily as the depth of the well increases.

The waters were also compared with regard to the proportional chemical values of the sulphates and chlorides, which together cause the saline quality of all these waters. (See section B.) The reader will observe that at 615 to 683 feet the saline quality of the water is almost wholly due to sulphates, the chlorides contributing not more than 8 per cent of the total salinity of the water found at that depth. From the layer between 636 and 720 feet the proportion of the sulphate salinity has been reduced to 69 per cent, and at 700 to 720 feet it is still further reduced, so that the saline quality of the water is shared equally by sulphates and chlorides.

From the progressive changes disclosed in the qualities of the waters in well 7-10, with increasing depth of the water sands, one would infer that the water in well 8-10 comes from a sand interme-

diate between the first and second water sands represented in well 7-10. The proper stratigraphic order for this sand is most likely immediately under the first member and not at the bottom of the table. A blank space has been left in the table to indicate this fact. One may also infer that the water sand in well 8-10 does not extend to well 7-10, but pinches out somewhere between the two wells.

This interpretation of the results of water analyses forewarned the company that somewhere between 713 and 720 feet below the top of the Big Blue shale, well 8-10 would encounter a water sand of 90-barrel daily flow. In order to obtain oil from a deeper sand in this well, a string of pipe would have to be cemented at a depth of at least 720 feet below the top of the Big Blue. This necessity

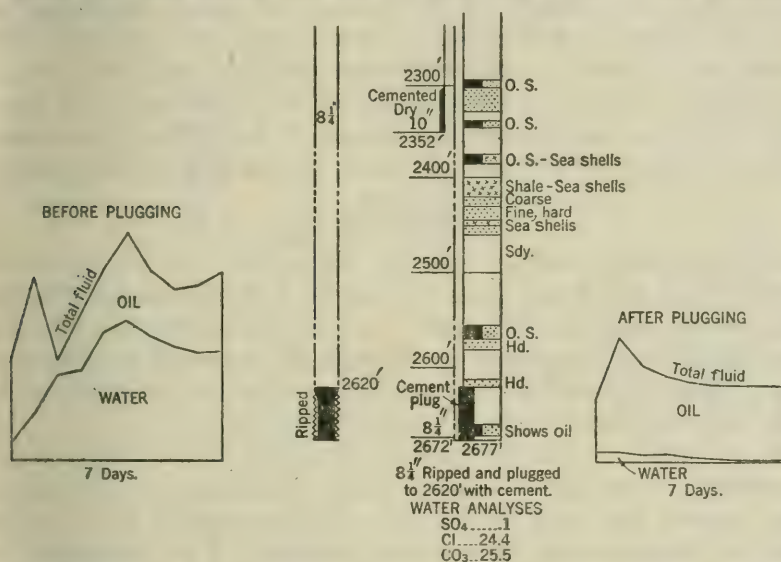


FIGURE 23.—Sketch showing production of oil well before and after plugging off bottom water. The source of the water was determined by chemical analysis.

might easily have been overlooked if the quality of the waters in well 7-10 had not been known. Furthermore, if well 8-10 had not been cemented at this depth, the water string would have been landed above a water sand, thus making it necessary for the company to cement another string of pipe at an additional cost of several thousand dollars.

It is safe to conclude that in this single instance the company considers the saving of labor, time, and money more than covered the cost of the few hundred dollars spent in sampling and analyzing the waters.

Example 2.

The well (see fig. 23) was drilled to 2,677 feet. All sands were perforated and the well started pumping. The well produced for

seven days, averaging 83 barrels of oil and 104 barrels of water daily. The production of water was a surprise, as it was the first time bottom water had been reported in this section. The volume of water would have been much more with a larger pump, but the 2½-inch pump would not handle more than 200 barrels of fluid per day. Had the water not been shut off it would have worked back into the oil sands and probably have done great damage.

An analysis of the water showed the reacting value of the sulphate radical to be 0.1 per cent, the chloride radical 24.4 per cent, and the carbonate radical 25.5 per cent. The bottom waters in this area were high in carbonates and chlorides and low in sulphates. The analysis thus indicated a decided bottom water. Accordingly, the lowest sand was plugged off by ripping the casing and filling the hole with cement up to the base of the next sand (at 2,620 feet). The cement was allowed to set eight days and the well again put to producing. The well then made 80 barrels of oil and 1 of water daily. In this case the analysis indicated the source of the water without mechanical tests and the repair work was done immediately.

Example 3.

The following example (see fig. 24) shows the use of water analyses in a well being drilled to test the different sands. The history of the work on this well is given in considerable detail to illustrate the care exercised in learning the contents of each sand. The purpose of these tests was to discover a new oil sand that might have been overlooked in the drilling of other wells.

On the left-hand side of figure 24, the work on the well is shown graphically in progressive stages. This sketch shows the relationship between the depth of the hole and the possible source of the water at the time any sample was collected. The percentages of reacting values of the radicals in different waters is shown at the right, each analysis being recorded opposite the sand in which the water occurs. These figures clearly show that the waters are distinctly different.

The 10-inch casing was cemented at 2,071 feet, the cement permitted to set, and a pocket drilled several feet below the casing shoe. Then the hole was bailed and stood dry for several hours, proving the water string was not leaking. This is indicated in the sketch by W.S.O., meaning water shut-off.

Drilling proceeded to a depth of 2,110 feet, when "sulphur water" came into the well, evidently from the 2,095 to 2,105 foot sand. In a bailing test made to test this sand, the water could not be bailed down lower than 1,340 feet from the surface, thereby proving that the sand carried a large volume of water. A sample of water taken for analysis showed the following reacting values: SO_4 , 28 per cent;

Cl, 10 per cent; CO_3 , 12 per cent; S, none; which were characteristic of a top water in this field.

The well was deepened to 2,215 feet, and a pumping test made after landing the 8 $\frac{1}{4}$ -inch casing at 2,207 feet with 119 feet of shop-perforated pipe on the bottom. The well pumped 1,080 barrels of "sulphur water" and no oil in four days.

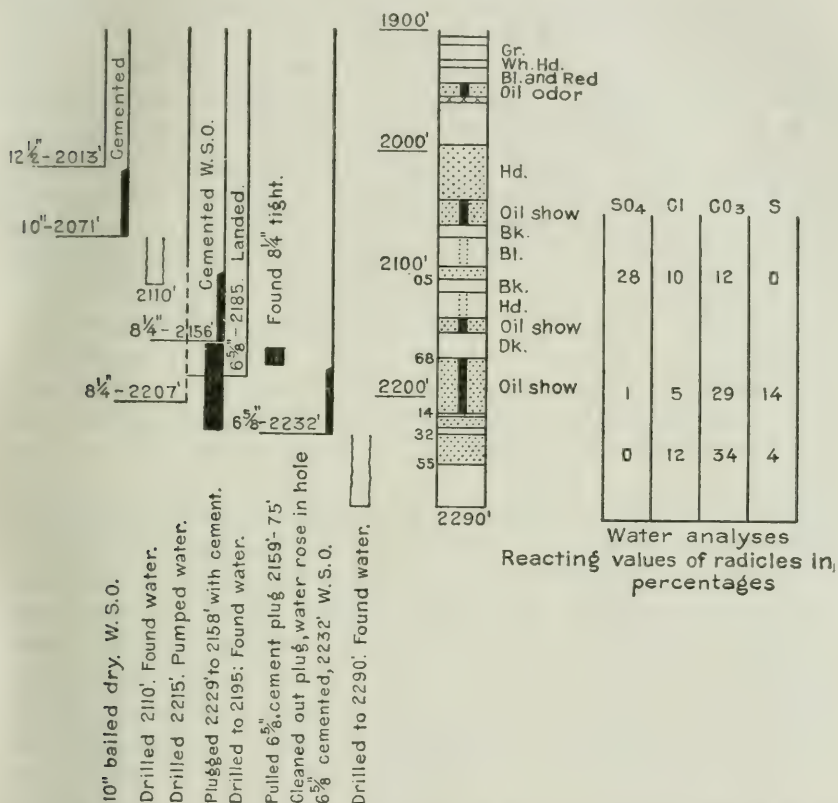


FIGURE 24.—Graphic sketch showing reacting values in percentage of radicals in waters of different sands and condition of hole when samples were collected. The results of the analyses are recorded opposite the sand in which the water was found. (See text.)

The operators then decided to shut off the water. The hole was deepened to 2,229 feet in order to free the 8 $\frac{1}{4}$ -inch casing, which was pulled, and a cement plug put in from 2,229 to 2,158 feet, after which the 8 $\frac{1}{4}$ -inch casing was landed at 2,156 feet and cemented. After the cement had set, a pocket was drilled and a bailing test made on the 8 $\frac{1}{4}$ -inch casing. The test was satisfactory and proved that the upper water was shut off.

In an effort to test the sand found at 2,168 to 2,214 feet, the cement plug was drilled out to 2,195 feet, after which the 6 $\frac{5}{8}$ -inch casing was

landed at 2,185 feet and the well bailed. The sand whose top was at 2,168 feet showed an enormous quantity of water; an analysis showed the following reacting values: SO_4 , 1 per cent; Cl, 5 per cent; CO_3 , 29 per cent, and S, 14 per cent. A glance at figure 23 will show that this water is entirely different from that in the sand 2,095 to 2,105 feet.

The company had expected oil from the sand 2,168 to 2,214 feet, and thought there might be a leak in the 8 $\frac{1}{4}$ -inch casing. The water analyses had indicated a new water sand, but at that time the company was just starting analytical work, and so far chemical analyses had not demonstrated their reliability. In order to check the suspicion that water was breaking around the 8 $\frac{1}{4}$ -inch casing, the operator decided to plug up to the bottom of this string and test it again. In the meantime sand heaved into the hole. This was cleaned out to 2,175 feet and a cement plug put in between 2,175 and 2,159 feet; that is, the top of the plug was 3 feet below the bottom of the 8 $\frac{1}{4}$ -inch casing. The well was again bailed dry, which proved that the water was not coming from around the 8 $\frac{1}{4}$ -inch casing and that the indications shown by the water analyses of there being a new water sand at 2,168 to 2,214 feet were correct. This plugging job could have been avoided if the company had used the results of water analyses.

The well when 2,159 feet deep made about 24 barrels per day of water, but when the hole was 2,175 feet deep the water could not be bailed down. The well was cleaned out to 2,178 feet and the water immediately rushed in. It could not be lowered more than 200 feet by fast bailing, again proving that it was coming in large volume from the sand whose top was at 2,168 feet. The well was deepened to 2,235 feet. The 6 $\frac{5}{8}$ -inch casing was landed and cemented at 2,232 feet in order to test out the sand whose top was at 2,232 feet. After the cement had set a pocket was drilled 4 feet below the casing shoe and the well bailed dry. It made practically no water when allowed to stand 19 hours, thereby proving that the water was shut off by the 6 $\frac{5}{8}$ -inch casing. The well was deepened to 2,290 feet and a bailing test made on the sand 2,232 to 2,255 feet. Some stratum of this sand made approximately 200 barrels of water in 24 hours. The water was not at the very top of the sand, because the well was bailed dry after drilling to 2,236 feet. A sample was collected whose analysis showed the following reacting values: SO_4 , none; Cl, 12 per cent; CO_3 , 34 per cent; S, 4 per cent.

A glance at the percentage figures at the right-hand side of figure 23 shows that this water is distinctly different from the two above it.

Additional work was done in completing this well, but the history is reviewed only to the point necessary to bring out the value of water analyses. The drillers reported oil showings in the sand 2,168 to

2,214 feet; whereas in fact the sand produced nothing but "sulphur water" when bailed vigorously.

The Shell Co., of California, has applied the results of water analyses on at least 18 wells, to the writer's knowledge, for detecting the source of water coming into the wells. The value of this work is difficult to express in dollars, but when the amount of oil that would have been lost if the water problem had not been solved is considered undoubtedly thousands, if not hundreds of thousands, of dollars were saved to that company. In operating expenses alone the sampling and analysis of waters has saved the company thousands of dollars, because when any oil well starts to make water an analysis will indicate the source of the water. Repair work can start without the delay and expense of testing. When the sample is edge water, the company does not waste time making expensive tests for top and bottom water.

APPLICATION OF WATER ANALYSES IN GULF COAST OIL FIELDS.

The writer understands that one of the large oil companies in the Gulf Coast oil fields has accomplished very successful results by the use of water analyses. An example of this work follows. A well that was perforated in two sands made water, which an analysis showed to be coming from the top sand. The top sand was shut off by setting a packer on the tubing below the top perforations. This packer filled the annular space between the tubing and the casing. (See right-hand diagram of fig. 18, p. 81.) After the packer had been set the well started flowing oil from the lower sand. This is but one of the several successful results accomplished in this work. Some of the wells came in flowing as high as 1,000 or more barrels of oil per day after corrective measures were taken, which had been suggested by the use of water analyses.

GENERAL SUGGESTIONS IN USE OF WATER ANALYSES.

COLLECTION OF SAMPLES OF WATER FROM WELLS FOR ANALYSIS.

A sample of water for analysis is of no value unless it is representative of the water found in the sand. The water sampled should not be mixed with drilling water, and a sample is of little value where several water sands are exposed in the hole. At the start of the work the engineer should collect samples of unmixed waters from each sand, if possible, so that he may know the properties of the waters in definite water sands. A 1-gallon sample of water is usually enough.

Where a producing well has made water for some time a true sample may be obtained from the flow tank or sump, as other water has been flushed out. If the well has just started to make water, and

other water has been in the tanks, then it is best to take a sample from the lead line.

In wells being drilled the engineer should grasp every opportunity to get a true sample of water from each sand. This can often be accomplished by collecting a sample from the first porous stratum encountered by the drill below the casing shoe. If the first sand does not yield water then a sample can be collected in a lower horizon. All drilling water should be bailed out of the hole, and a sample taken from the bailer after it has been run to bottom.

APPLICATION.

After a sample is collected and a chemical analysis made the engineer should interpret the analysis according to Palmer's method (see pp. 91 to 97). When there are several analyses a tabulation should be made of the properties of the waters in known sands and of the distances of these sands from the marker. Then when a well starts to make water its source can be determined by comparing its chemical properties with those in the tabulation. The use of water analyses is, therefore, a matter of comparison.

EACH FIELD A SEPARATE PROBLEM.

The waters of each oil field are chemically different from those of another field. In Coalinga, Calif., the writer used both the properties of reaction and the character formula for comparing different waters.

Neal⁴⁶ reported that the content of solids in the top waters of the Augusta field (Kans.) averaged four or five times that in the bottom waters. In fact, so marked was the difference in specific gravity that J. O. Lewis, chief petroleum technologist of the Bureau of Mines, suggested that a hydrometer might be used to distinguish between these waters.

Rogers,⁴⁷ in commenting on Neal's paper, discusses the difference between Mid-Continent and California oil field waters.

The engineer will find certain distinguishing features in the chemical analyses of water from the same field that will serve to identify the waters in one sand from those in another.

The character formula, as well as the properties of reaction, must often be considered in comparing different waters. This is brought out by the writer's experience in Coalinga, Calif. The top waters were low in chlorides, but high in sulphates. Thus, the top waters would have a high primary salinity percentage. The bottom waters were practically free of sulphates, but high in chlorides. The high

⁴⁶ Neal, R. O., Petroleum hydrology applied to Mid-Continent field: Bull. Am. Inst. Min. Eng., Feb., 1919, pp. 3-4.

⁴⁷ Rogers, G. S., Discussion on "Petroleum hydrology applied to Mid-Continent field," by R. O. Neal: Bull. Am. Inst. Min. Eng., March, 1919, pp. 603-606.

chloride content gave bottom waters a high primary salinity. Hence, both top and bottom waters had a high primary salinity percentage, but a glance at the character formula readily told whether a sample was top or bottom water.

FORM FOR COMPUTATIONS.

The converting of the results of an analysis of water into reaction values according to Palmer's method can be done more easily on a form like Form 3. On a sheet 8½ inches by 11 inches are printed the factors, formulas, etc., shown in roman type in Form 3. The items in italics represent the computations of an analysis. After the computations are made the sheet can be filed for future reference.

FORM 3.—Form for computing water analysis, as reported by the analyst, to Palmer's method of interpretation.

Analyst.....		Company WATER ANALYSIS.				Sample No..... Well No..... Date taken.....			
(1)	Grains per U. S. gallon. (2)	Factor. (3)	2 × 3 (4)		2 - 4 (5)		(a)		
Na ₂ SO ₄ ..	18.41	0.324	Na..	5.97	SO ₄ ..	12.44			
Na Cl...	6.25	.393	Na..	2.06	Cl...	3.19			
Na ₂ CO ₃ ..	106.45	.434	Na..	46.20	CO ₃ ..	60.25			
Na ₂ S...	7.34	.589	Na..	4.32	S...	3.02			
Ca SO ₄ ..	1.00	.294	Ca..	.29	SO ₄ ..	.71			
Ca Cl ₂ ..	0.	.361	Ca..	0.	Cl ₂ ..	0.			
Ca CO ₃ ..	1.80	.400	Ca..	.72	CO ₃ ..	1.08			
Mg SO ₄ ..	.39	.202	Mg..	.08	SO ₄ ..	.31			
Mg Cl ₂ ..	0.	.255	Mg..	0.	Cl ₂ ..	0.			
Mg CO ₃ ..	1.43	.288	Mg..	.43	CO ₃ ..	1.05			
Na	Ca	Mg	(a)	SO ₄	Cl	CO ₃	S	(a)	(a)
5.97	0.29	0.08		12.44	3.19	60.25	3.02		
2.06	.72	.43		.71		1.08			
46.20				.31		1.05			
4.32									
Total (a)	58.55	1.01		13.46	3.19	62.38	3.02		
Reaction coeff. (b)	.0435	.0499	.0822	.0208	.0282	.0333	.0624		
(a × b)	2.547	.050	.042	.280	.090	2.077	.188		
Total (a × b) = 5.274									
Reacting value, per cent.....1	48.3	0.9	0.8	5.3	1.7	59.4	3.6		
PRIMARY SALINITY: SO ₄ + Cl = 7.0, with equal value Na (K) = 14. SECONDARY SALINITY: (If SO ₄ + Cl greater than Na (K)), then SO ₄ + Cl = ..., with equal value Ca + Mg = PRIMARY ALKALINITY: Excess Na (K) over SO ₄ + Cl = 41.3, with equal value CO ₃ + S = 82.6 SECONDARY ALKALINITY: Excess Ca + Mg over SO ₄ + Cl = 1.7, with equal value CO ₃ + S = 3.4 CHLORIDE SALINITY: Cl ÷ (SO ₄ + Cl) = 0.243 × 100 per cent = 24.3 SULPHATE SALINITY: SO ₄ ÷ (SO ₄ + Cl) = 0.767 × 100 per cent = 75.7 Depth of well: Method of procuring sample: Remarks:									

a Blank column for additional entries if desired.

SELECTED BIBLIOGRAPHY.

The method for converting the results of water analyses into reacting values, character formula, and reaction properties of the solution is given in detail in several publications. Some of the publications on this subject are listed below:

- PALMER, CHASE. The geochemical interpretation of water analyses: U. S. Geol. Survey, Bull. 479, 1911, 31 pp.
- VAN WINKLE, W., Quality of the surface water of Washington: U. S. Geol. Survey, Water Supply Paper 339, 1914, 105 pp.
- Quality of the surface waters of Oregon: U. S. Geol. Survey, Water Supply Paper 363, 1914, 37 pp.
- CLAPP, C. H., Sharp point hot spring, Vancouver Island, B. C.: Canada Geol. Survey, Summary Report for 1913. 1914, pp. 80-83.
- SIEBENTHAL, C. E., Origin of zinc and lead deposits of the Joplin region: U. S. Geol. Survey, Bull. 606, 1915, 283 pp.
- ROGERS, G. S., The interpretation of water analyses by the geologist: Econ. Geol., vol. 12, Jan., 1917, pp. 56-88.
- Chemical relations of the oil-field waters in San Joaquin Valley, California: U. S. Geol. Survey, Bull. 653, 1917, p. 119.
- ELWORTHY, R. T., Mineral Springs of Canada: Canada Department of Mines, Bull. 20, 1918, 173 pp.
- NEAL, R. O., Petroleum hydrology applied to Mid-Continent field: Bull. 145. Am. Inst. Min. Eng., January, 1919, pp. 1-8; discussion by G. S. ROGERS March, 1919, pp. 603-606, Bull. 147.

USE OF DETECTORS FOR TRACING MOVEMENT OF UNDERGROUND WATERS.

GENERAL REMARKS.

The rate of movement of underground waters is largely dependent upon the character of the sand—whether it is a coarse sand having large voids, or a fine, tight sand, and whether it consists in part of silt or other fine material. Mills' work (see discussion on pp. 70 to 72, and Pls. XVI and XVII) indicates that water under pressure flows more freely through the coarser sands. The rate of flow, however, varies with many other factors, such as the porosity of the sand, the temperature of the water, the distance the water must flow through the sand, the effective size⁴⁸ of the sand grain, and the difference in pressure at either end of the channel through which the water must pass.⁴⁹

Some idea of the rate of flow of water from one well to another may be gained by the use of dyes and other flow detectors. The

⁴⁸ A term used by Slichter, C. S., The motion of underground waters; Water Supply Paper 67, U. S. Geol. Survey, 1902, p. 22, to designate the mean diameter of a grain, an aggregate of which in one body would have the same transmission capacity as the sand or soil under consideration.

⁴⁹ See Slichter, C. S., work cited; also his paper on Field measurements of the rate of movement of underground waters; Water Supply Paper 140, U. S. Geol. Survey, 1905, pp. 10-15.

rate of flow from well to well is determined by dividing the distance between the two wells by the time required for the detector to travel in the water from one well to another. Very little information is available on the flow of waters 2,000 feet or more below the surface, such as oil-field water.

King⁵⁰ has furnished some interesting data on the change caused in the water level of a well by pumping another well 1,133 feet away. Both wells were about 70 feet deep and 6 inches in diameter. When one well was pumped intermittently for several hours the total fall in the water level in the second well was three-fifths of an inch. The experiment was repeated several times, showing that the fall of water in the second well began 1 hour and 45 minutes after the pump was started in the first well.

Water may come into an oil well from various sources (see pp. 134 to 139), and thence get into an oil sand from which other wells are producing, thereby causing considerable damage. In efforts to trace such water from one well to another several means have been used and others suggested. Certain flow detectors, such as dyes, have been used with a fair degree of success in some oil fields.

If the detector placed in one well appears in another well, it indicates the direction and rate of travel of the water; but if the detector does not appear, nothing is established. The chemical and physical effects to which the detecting substance will be subjected underground can not be predicted and may entirely change its properties and appearance; hence when the substance fails to appear there is no way of knowing whether it did or did not pass into the sand. The general conclusion reached by many operators and chemists who have used dyes is that just stated—when the dye actually travels from one well to another definite conclusions may be reached; but if the indicator does not appear in adjoining wells, the problem is no nearer solution. In the latter event the operator makes little real headway in solving his problem, although possibly satisfied in his own mind that the damaging water does not come from the well in which the detector was placed.

The best of dyes are not infallible, primarily because of the uncertainty as to whether the dye penetrates effectively into the sand or is destroyed under ground. The success of the dye test is fundamentally based upon the proper introduction of the dye into the sand through which the water flows; mechanical and other means for insuring this result can probably be developed. Wells where the detector is expected to show should be pumped as fast as possible in order to draw the water toward the well.

⁵⁰ For description of work and recording instruments used see King, F. H., Principles and conditions of the movements of ground water: 19th Ann. Rept., U. S. Geol. Survey, pt. 2, 1899, pp. 277-279.

Many waters, pumped or flowing out of a well with the oil, contain metallic salts of naphthenic acids or other organic matter in true or colloidal solution: hence they have a yellowish brown or orange color in neutral or alkaline solutions and a yellow color in acid solution. This natural color will certainly obscure or interfere with any dyes. It can be destroyed by oxidation with dilute potassium permanganate in acid solution, any excess permanganate being reduced with oxalic acid, but whether the dyes will survive such treatment is questionable.

Methods that have been used and suggested for determining the movement of underground waters are:

1. Dyes and other materials recognized by their color.
2. Chlorides, nitrates, or other salts recognized by chemical analyses.
3. Lithium salts, which can be detected by the spectroscope.
4. Slichter electrical method.

REQUIREMENTS OF A DETECTOR.

In all the methods mentioned an artificially introduced substance that can be detected must be carried from one well to another by water: hence it is important that the flow detector travel at the same rate as the water itself—that is, the detector should not settle or filter out. The detectors used should be readily soluble in water and should be stable substances that will not lose the physical or chemical properties by which they are detected through reacting with the salts or other materials present in the water or sands with which they come in contact. They should be substances that are easily detected and that do not occur naturally in the waters under investigation. Substances recognized by their color appeal to the operator because they can be seen easily, whereas in using salts the operator must take the results of a chemical analysis or other test for the detection of the ion introduced. As is brought out later, fluorescein meets those requirements better than any other substance known, because it can be detected in extremely dilute water solutions and requires no expensive equipment or elaborate tests for its detection.

ORGANIC DYES AS DETECTORS.

Oil-field operators customarily refer to fluorescein, eosine, and other organic dyes as "aniline dyes," although some of these are derived from substances other than aniline and in a strict sense are not aniline dyes.

The objections to the use of dyes are (1) that oil-field waters are often colored from organic matter and there is the possibility that this color can not be destroyed without destroying any dye that might

be in the water; (2) a dye may be filtered out of the water, especially by adsorption in passing through finely divided material for distances of 100 feet or more, or it may be chemically decomposed by the high salinity of the ground waters, and the action of sulphur dioxide, hydrogen sulphide, sodium carbonates, or organic compounds present in the formations through which the dye may pass.

Fluorescein, eosine, methylene blue, magenta or fuchsine, and Congo red have been suggested for use. A description of the various dyes may be found in any comprehensive book on organic chemistry. Dyes of possible use in tracing underground waters in oil fields are briefly discussed here for the purpose of pointing out to the operator what dyes will be most satisfactory and indicating the difficulties and limitations of various dyes with different types of waters.

COMPARATIVE VALUE OF VARIOUS ORGANIC DYES FOR OIL-FIELD USE.

As previously stated, the success of any dye for tracing underground waters depends upon its proper introduction into the sand carrying the water. Unless the dye enters the sand it can not show in adjoining wells.

The value of the different dyes for the use proposed has been well summarized by Merz.⁵¹

We believe that fluorescein is the best that can be used. Mr. W. A. Ambrose suggests fluorescein, eosine, methylene blue, magenta, and Congo red. Congo red is too sparingly soluble. Methylene blue and magenta are basic colors, and all basic colors are adsorbed by clays, and are therefore unreliable. Fluorescein and eosine are not adsorbed by clays.

We suggest the sodium salt of fluorescein as most reliable. An excess of soda will not be harmful, and the final sample of water that is drawn should be tested for acidity; it should be made alkaline with sodium carbonate, and if discolored by suspended matter that might obscure the color it can be filtered. The use of acetic acid in bringing dyes in solution would apply only in using basic colors, such as fuchsine or methylene blue. As already stated, filtration through clay will remove both these colors.

It is generally agreed that fluorescent dyes are the most satisfactory for determining the movement of underground waters, as they are the most easily detected in minute quantities. Of the various dyes discussed, only fluorescein, eosine, and magenta are fluorescent; the limitations of other dyes, both organic and inorganic, are mentioned on subsequent pages. Of the three fluorescent dyes, magenta offers the least promise. Eosine has merits, but fluorescein is, perhaps, the most dependable.

⁵¹ Personal communication, Dr. Eugene Merz, of Heller & Merz Co., American Ultramarine and Globe Aniline Works, Newark, N. J., to W. E. Perdew, Union Petroleum Co., Philadelphia, Pa., July 24, 1919.

FLUORESCEIN.

Fluorescein ($C_{20}H_{12}O_5$) is a weak acid and represents the type of detector that can be easily recognized by its color (yellowish brown) when dissolved in large volumes of water. When present in dilute quantities in a solution of clear water, it shows a magnificent yellowish-green fluorescence by reflected light, which may appear colorless by transmitted light. This dye is almost colorless in dilute solutions containing free acid (except carbonic), hence the dye is more certain to be recognized if the solution is made slightly alkaline.

Probably fluorescein is superior to all other dyes, because it is noticeable when present in minute quantities and is not adsorbed by clays. Fluorescein will penetrate an acid solution further than eosine and give a color reaction that eosine may fail to give. Also it is not affected by sulphureted hydrogen and sulphurous acid.

It diffuses very rapidly and can be detected with the naked eye when present in the ratio of one part in 40,000,000.⁵² By means of the fluoroscope it can be detected in amounts varying from one part in 500,000,000 to one part in 10,000,000,000 of clear water, but the practical limit of the fluoroscope is one part in 2,000,000,000, provided the water is pure and perfectly clear. If the liquid is muddy, filtering before observation is necessary.

EXPERIMENTS WITH FLUORESCEIN IN FRANCE.

Extensive experiments have been made in France with fluorescein to determine the underground movement of different waters and the rate of flow. Dole⁵³ has reviewed these experiments and the following description is taken largely from his paper.

Fluorescein solution was added to sink holes near the watersheds, wells, springs, etc., and samples of water collected in near-by localities to learn whether the movement of the water could be traced. The amount of fluorescein used varied from 2 to 4 pounds, according to the distance and the material to be traversed. The rate of flow was determined by dividing the distance between the upstream point where the fluorescein was added and the downstream point where the samples were collected by the length of time it took the dye to travel that distance.

Some of the distances were surprisingly long, as the tabulation shows. The formations traversed were loam, limestone and millstone, clay, and Champigny travertine. The latter was much fissured and at places contained large caverns.

⁵² Dole, R. B., Use of fluorescein in the study of underground waters: Water Supply Paper 160, U. S. Geol. Survey, 1906, p. 76.

⁵³ Dole, R. B., Use of fluorescein in the study of underground waters: U. S. Geol. Survey Water Supply Paper 160, pp. 79-83.

Results of experiments with fluorescein.

DHUIS REGION.

Experi- ment No.	Fluores- cein used.	Maxi- mum dis- tance traveled.	Differ- ence in elevation.	Time elapsed.	Rate of flow.
	<i>Pounds.</i>	<i>Feet.</i>	<i>Feet.</i>	<i>Hours.</i>	<i>Feet per minute.</i>
1.....	1.1	10,332	166	14	12.3
2.....	.66	8,856	164	18	8.2
3.....	2.64	18,532	188	32	9.6
4.....	1.76	10,824	117	12	15
5.....	.22	1,640	40	5	5.5
6.....	1.98	8,856	.....	14	10.5

YONNE AND CURE REGION.

1.....	0.6	492	.....	24	a 0.34
2.....	6.6	19,680	230	72	4.6
3.....	2.2	4,100	.....	1.25	55
4.....	4.4	38,212	.....	59	10.8
5.....	4.4	43,558	328	222	3.3

a Compact limestone.

In experiment 1, of the Yonne and Cure region, fluorescein placed in a 160-foot well worked about 500 feet through a compact limestone in 24 hours, its rate of flow being much slower than in experiment 2, where it traveled through the surface soil. The other experiments were conducted in very porous surface soils or cavernous formations in which the rate of flow is much greater than would be expected in the most porous water sands of oil fields. Experiment 1, in the Yonne and Cure region, is more comparable to water conditions in oil fields.

USE OF FLUORESCIN WITH THE AID OF THE FLUOROSCOPE.

In connection with the water supply of the city of Paris, fluorescein was used successfully in tracing the movement of underground waters over long distances. The fluoroscope was used in this study. Some remarkable results were obtained which indicate that fluorescein will travel a great distance underground without losing its color; also that fluorescein retains its color in traveling through lime, sand, clay, and farm manure, but is decolorized by peaty soils.

FLUOROSCOPE.

The fluoroscope used by Marboutin,⁵⁴ of the Montsouris laboratory, has 12 glass tubes, 95 cm. long and 15 mm. in diameter, each tube being closed at the bottom with a darkened rubber stopper. The samples of water to be tested are placed in the tubes and examined

⁵⁴ Marboutin, M., Contribution à l'étude des eaux souterraines: Compt. rend., t. 132, 1901, p. 365.

by looking down through each tube along its axis. The presence of fluorescein is revealed by a greenish fluorescence which shows against the blackened stopper. For comparison, a sample containing a known amount of fluorescein may be used in one of the tubes. In order to perceive the slightest fluorescence care should be taken that the apparatus is not mounted on green and that there is no green color in the background.

EOSINE.

Eosine ($C_{20}Na_2H_6Br_4O_5$) is the sodium salt of bromo-fluorescein. Pure eosine is brick red. It is slightly soluble in water and with alkalis forms salts that dissolve easily in water. The commercial product is usually a sodium salt which is very soluble in water and has a strong yellow fluorescence. The mineral acids, such as sulphuric (H_2SO_4), hydrochloric (HCl), and nitric (HNO_3), decompose eosine, so in examining solutions for the presence of eosine the liquid should be made slightly alkaline. Eosine is not adsorbed by clays.

METHYLENE BLUE.

Methylene blue (empirical formula $C_{16}H_{18}N_3SCl$) is ordinarily a dark blue or reddish brown powder with a bronze reflection, and when dissolved in water forms a blue solution. The color is not changed in the presence of ammonium hydroxide or dilute acids. Although methylene blue is a very stable compound, it would not be as satisfactory as fluorescein for determining the movement of underground waters, as it can not be detected in such minute quantities; furthermore, it is a basic color. All basic colors are adsorbed by clays and are, therefore, unreliable.

MAGENTA.

Magenta is a dark green, crystalline powder, also known as fuchsine, aniline red, and rubine. It is only slightly soluble in cold water, but more so in hot water. When in solution it gives a beautiful crimson fluorescent color. Its low solubility may be an objection to its use; also the ordinary commercial produce can not be used in alkaline waters. Furthermore, magenta being a basic color is adsorbed by clays, and hence is unreliable.

CONGO RED.

Congo red as marketed is a brown powder that produces blood-red solutions when dissolved in pure water or in alkaline water, but turns blue with acid. Under the most favorable conditions this dye is not

as easily detected as fluorescein or eosine. Congo red is too sparingly soluble in acid solution, and if it met acid waters it would be precipitated and filter out.

INORGANIC DYES AS DETECTORS.

Besides organic dyes, certain inorganic substances, such as potassium dichromate and Venetian red, have been suggested as flow detectors.

POTASSIUM DICHROMATE.

Potassium dichromate ($K_2Cr_2O_7$) dissolves in water very readily, forming a yellow solution when dilute. To color a liter of water to No. 21 Saybolt color, which is the standard for "water-white" kerosene requires 0.0048 gram of potassium dichromate. Any concentration greater than that proportion can be detected by the naked eye, but in much lower concentrations the dye is difficult to detect even with a colorimeter. Its value for use in tracing oil-field waters is questionable, because many oil-field waters have a yellowish tint, because it is decolorized by reducing agents, such as hydrogen sulphide, and because an excessively large quantity would be required to color a large volume of water.

VENETIAN RED.

Venetian red is a common earthy variety of hematite (ferric oxide), a well-known form being rust. This pigment has a limited application in oil wells, as it does not dissolve in water and would filter out quickly when passing through a sand. Sometimes venetian red is placed in the fluid behind the water string at the time the casing is landed. When the water string is tested for dryness or pumping is started the venetian red will probably show in any water coming around the casing shoe or through a leak in the pipe.

PRACTICAL APPLICATION OF DYES IN OIL FIELDS.

WHEN USED.

In determining the movement of oil-field waters dyes or other flow indicators have two general uses—to determine whether water is coming into the well through a leak in the casing or around the shoe of the water string and to determine whether water is migrating from one well to another.

In testing the water string for leaks the dye or other material is placed outside this string, and from time to time the fluid bailed or pumped is examined to see whether the dye has worked into the

well. Its appearance in the well would be proof of a leak in the water string, but its failure to appear does not prove that the shut-off is effective, because cavings may have lodged around the pipe at some point, thus holding the dyed water back.

Sometimes Venetian red is placed behind the water string when it is landed, with the idea that if at any future time the water string should leak the dye will come through. For this use an insoluble dye, such as Venetian red, is better than a soluble one.

In studying water migration from well to well the dye, generally as a solution, is put in a proper container and placed near the bottom of the well, in order to prevent its dilution with the long column of fluid in the hole. The dye is placed in the well that seems to be flooding the other well or wells; often production is suspended at this well during the test so that the dye will not be pumped out. Neighboring wells should be pumped vigorously and the water closely watched for any evidence of the dye's appearance.

PLACING OF DYE IN WELL.

The dye should be dissolved in a bucket of water. For testing a leaky water string, the dye can be poured around the outside of the casing and washed down with a hose.

For a test at the bottom of the hole, a solution of the dye may be placed inside a glass container (R. E. Collom, petroleum technologist, Bureau of Mines, has used a large demijohn) and lowered on the bailer or bit. The container can be broken there by a blow with the dart of the bailer or with the bit.

QUANTITY USED.

The amount of dye used for any particular test can best be determined by experiment; it will depend largely on the water the well or wells are making. Dyes differ in sensibility and usually the operator will have to use a commercial dye of unknown sensibility. The following method indicates how the sensibility of a commercial dye, whose composition was unknown, was determined by Harry H. Hill, refinery engineer, Bureau of Mines. The particular dye was "acid orange No. 369;" it cost at the time about 90 cents a pound.

One-tenth of a gram was mixed with 1,000 c. c. of water, giving a concentration (by weight) of one part per 10,000. The solution was thoroughly shaken and 100 c. c. was diluted with 1,000 c. c. of water, making the concentration of one part to 100,000, which gave a strong color easily detected in clear water. As a barrel of water weighs approximately 350 pounds, to obtain a concentration of one

part per 100,000, divide 350 by 100,000. In other words it requires 0.0035 pounds of dye to the barrel of water, and 100 barrels of water would require 0.35 pounds.

Enough dye should be placed in a well to bring about this concentration in the water coming from the "water" wells in a 12 to 24 hour period. That is, if one well was making 100 barrels of water per 24 hours, enough of this particular dye should be added to the well suspected of furnishing the water to make a concentration of one part in 100,000. In this case at least 0.35 pounds should be added in solution form.

Other tests on this dye with various substances, such as sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium carbonate (Na_2CO_3), hydrochloric acid (HCl), salt water, hydrogen sulphide, and crude petroleum indicated that they would not change or destroy the color of the dye.

USE OF ORGANIC DYES IN OIL FIELDS OF CALIFORNIA.

In most tests the use of dyes has not been entirely satisfactory. If the dye shows in a neighboring well, the results are positive; if it does not, nothing is proved. Some tests in California are cited here as examples of what may be expected in the use of organic dyes.

KERN RIVER FIELD.

An indication of the rate of travel of underground water and concrete evidence of one well flooding another were shown in some tests in the Kern River field, near Bakersfield. Tom Saine, superintendent of the Petroleum Development Co. (Santa Fe), informed the writer that an aniline dye dissolved in water had traveled from Alma Jr. well No. 2, section 4, T. 29 S., R. 28 E., to Petroleum Development Co. well No. 18, section 4, T. 29 S., R. 28 E., a distance of about 1,000 feet, as rapidly as he could walk the distance. Well 18 was making about 1,000 barrels of water a day by the use of compressed air. This test was made before correction of water troubles in this well.⁵⁵

SANTA MARIA FIELD.

J. C. Knoke used aniline dyes in two wells in the Santa Maria field. These wells were 300 feet apart and about 2,700 feet deep. Dye was placed in one well, but did not show in the second well after an observation lasting a week or 10 days. Dye was then placed outside the water string in the second well, and in about three hours

⁵⁵ See Second Annual Report of the State Oil and Gas Supervisor of California, 1916-1917: Calif. State Mining Bureau, Bull. 82, 1918, pp. 255-260.

came up inside the casing, proving that the water string was at fault. When the water string was pulled, a hole was found in it. The water string was repaired.

OLINDA AND SALT LAKE FIELDS.

John T. Wooton, manager of the Amalgamated Oil Co., Los Angeles, Calif., advised ⁵⁶ the writer of the use of dyes by his company in the Olinda and Salt Lake fields.

In 1907, aniline dye was put in Salt Lake well 309 and was later detected in water from well 307, which was 680 feet distant.

In 1912 aniline dye was placed outside the water string of West Coast well 47, Olinda division, but no evidence of the dye was detected in other wells.

In 1914 aniline dye was put in West Coast well 36, as the Olinda Land Co. claimed this well was furnishing water to its No. 9 well of Mr. Wooton's company, 150 feet away. No evidence of the dye was found in No. 9.

Dye was also placed behind the water string in the Anaheim well, but no results were obtained.

Of the five trials of dye, only one was conclusive.

MIDWAY FIELD.

Aniline dyes were tried in the Midway field in 1912 and 1913. Positive results were obtained in some of the tests, but on the whole the tests were not satisfactory. Sometimes negative results with dyes may be due to the fact that the water is not coming from the well suspected and to which the dye has been added, hence the dye has no chance to travel. In those tests where the dye appeared in adjoining wells, the color was unmistakable and furnished conclusive proof that the water traveled from one well to another.

An interesting check with red and green organic dyes was used in Chanslor-Canfield and Midway Oil Co. (now Santa Fe) well No. 9, in section 36, T. 31 S., R. 22 E. On August 28, 1913, red dye was placed in this well; it appeared the following day in American Oilfields Co. well No. 68, traveling a distance of approximately 900 feet. Two weeks later green dye was again placed in well 9; it appeared in well 68 within 3 hours and 15 minutes.

Table 2, compiled from information furnished by G. S. Rogers, geologist, United States Geological Survey, shows the number of tests tried in that district and the results.

⁵⁶ Personal communication, Apr. 14, 1919.

TABLE 2.—Results of use of organic dyes in Midway field, Calif.

Well.	Dye used, weight (pounds) and color.	Date put in.	Date detected.	Well, where detected.	Distance traveled (feet).	Remarks.
Am. O. 60....	20 red.....	Aug. 9, 1912....	.....	None.....	.....	Pumped out all dye from No. 60 on Aug. 29.
Am. O. 61....	..do.....	May 4, 1912....	.....	..do.....	.....	C. C. M. O. found no dye in neighboring wells. Bailed dye out of No. 61 on Aug. 5, 1912.
C. C. M. O. 8..	10 red.....	Aug. 8, 1912....	Aug. 14, 1912....	Am. O. 67..	350	Well idle until Oct. 6, 1913. Pumped red until Oct. 9, 1913. No trace in other wells. Remained bright green until Sept. 12, 1913. Record states "found red color in tank by No. 58" (presumably Am. O. No. 58).
Am. O. 67....	50 red.....	Sept. 23, 1912....	.....	None.....	.....	
Do.....	..do.....	Oct. 4, 1912....	.....	..do.....	.....	
C. C. M. O. 9..	(?) green..	Sept. 11, 1913, 10.30 a. m.	Sept. 11, 1913, 3.15 p. m.	Am. O. 73..	350	Record states "found red color in tank by No. 58" (presumably Am. O. No. 58).
C. C. M. O. 8..	100 red....	July 20, 1913....	Aug. 23, 1913....	Am. O. 58..	1,500(?)	
C. C. M. O. 9..	(?) red.....	Aug. 28, 1913....	Aug. 29, 1913....	Am. O. 68..	960	Water green in No. 68 on Sept. 12, 1913.
Do.....	(?) green..	Sept. 11, 1913, 10 a. m.	Sept. 11, 1913, 1.15 p. m.	..do.....	900	
C. C. M. O. 12.	100 red....	June 5, 1913....	.....	None.....	.....	All C. C. M. O. and Am. O. wells tested. No results.
Do.....	..do.....	June 12, 1913....	.....	..do.....	.....	
Do.....	25 red....	Sept. 13, 1913....	.....	..do.....	.....	
C. C. M. O. 16.	15.....	Mar. 22, 1914....	.....	No record..	.....	Put dye between casings.
Do.....	15.....	..do.....	.....	..do.....	.....	Outside casings.
Do.....	20.....	Mar. 25, 1914....	.....	..do.....	.....	Through tubing to bottom well.
C. C. M. O. 17.	12 green...	Mar. 8, 1914....	.....	..do.....	.....	Put dye between casings.
Do.....	15 red....	Mar. 22, 1914....	.....	..do.....	.....	Do.
T. M. O.....	30 red....	June 1, 1912....	.....	None.....	.....	M. R. O. claimed T. M. O. well was flooding theirs.
Do.....	15.....	Sept. 1, 1913....	.....	..do.....	.....	No trace of dye.
C. C. M. O. 2a..	35 green...	Nov. 1, 1913....	Nov. 22, 1913....	M. O. 5....	800	Continued green for 24 hours.
Do.....	20 green...	Dec. 15, 1913....	.....	.....	.....	No record of result.
Do.....	15 green...	Apr. 11, 1914....	.....	.....	.....	Do.

^a C. C. M. O., sec. 17, T. 32 S., R. 23 E.

NOTES.—Trade name of dye, "S. F. Green."

Am. O.: American Oil Fields Co., sec. 36, T. 31 S., R. 22 E.

C. C. M. O.: Chanslor-Canfield & Midway Oil Co. (Santa Fe), sec. 36, T. 31 S., R. 22 E.

T. M. O.: Toronto Midway Oil Co., sec. 18, T. 31 S., R. 23 E.

M. R. O.: Midway Royal Oil Co., sec. 19, T. 31 S., R. 23 E.

M. O.: Midland Oil Co., sec. 16, T. 32 S., R. 23 E.

COALINGA FIELD.

Fluorescein was used by the Shell Co., of California, in the fall of 1915 to test a leaky water string. The dye was placed behind the casing, but after extensive bailing tests the dye did not show. Later work showed that the water was coming from below the shoe of the water string.

THE USE OF CHLORIDES AND OTHER SALTS TO DETERMINE UNDERGROUND FLOW.**CHLORINE METHOD.**

The so-called "chlorine method" of determining the movement of underground water has been used, but its value in oil-field water problems is doubtful, primarily because all oil-field waters contain chlorides and many contain them in large concentrations.

This method was used successively by A. Thiem in a study of movements of underground waters near Leipzig, in Saxony. Also satisfactory results were obtained during a study of the new water-supply system at Greiswald and Stralsund, in Pomerania.⁵⁷

A salt that is determined easily by chemical means is placed in an upstream well and water from downstream wells is analyzed occasionally in order to detect the salt. Ordinary salt (sodium chloride) was used by Thiem at Leipzig, as it had the advantage of not injuring the water.

It is well known that salts when dissolved in a body of water at rest diffuse concentrically in every direction from the point of introduction, but if the water is in motion the diffusion on the horizontal plane resembles the outline of a pear, with the small end at the point of introduction and the axis extending along the direction of the flow. The salt will be detected in the downstream wells in small quantities at first, but will gradually appear in greater quantities. When the concentration of salt in two downstream wells is equal, a rough idea may be gained at the proportional rate of flow between each of these wells and the one upstream.

Evidently, as many analyses are necessary, the chemical test for determining the presence of salt must be simple and rapid. Because of the number of samples and the difficulty of analyzing them, it is doubtful if this method will be used to any extent. Another objection is that the presence of salt in a downstream well can not be detected by color or odor and the operator must rely on the analysis. Before a chloride is used the normal chloride content of the water from the wells must be determined, and the succeeding tests must be quantitative, as chlorine is always present.

Other substances besides common salt suggested for use in the chlorine method are calcium chloride (CaCl_2), and ammonium chloride (NH_4Cl), but neither of these salts has any particular advantage over common salt.

⁵⁷ Slichter, C. S., The motion of underground waters: Water Supply Paper 67, U. S. Geol. Survey, 1902, pp. 46-48.

NITRATES.

It has been suggested that nitrates be used as flow detectors. Practically all nitrates are readily soluble in water, but their use is not to be recommended because it requires a well-equipped laboratory and a skilled chemist, both of which are rare in ordinary oil-field practice. If nitrates are used, the water should be tested for their presence prior to their use. On comparing the use of nitrates with that of fluorescein, in which the color is evident to anyone, it is easy to see that for ordinary purposes the use of fluorescein is simpler.

Underground conditions may bring about the reduction of nitrates to nitrites or even to ammonia, for both of which there are delicate chemical tests.

LITHIUM SALTS AS DETECTORS.

It has been suggested that lithium salts be used as flow detectors, because these salts, except the carbonates, fluorides, and phosphates, are readily soluble in water and because they do not generally occur in oil-field waters. All salts of lithium that might in any way be formed in underground conditions in oil fields are soluble enough to give a solution which, upon concentration and proper treatment, will give the lithium lines with the spectroscope. The determination of lithium by aid of the spectroscope is positive.

After the water samples have been collected they must in some cases be concentrated and certain metals removed before a test is made by the spectroscope. The objections to the use of such a method are that it requires a laboratory, an expensive instrument—the spectroscope—and an experienced man.

SLICHTER ELECTRICAL METHOD.

Slichter has described⁵⁸ a method of measuring the velocity and direction of flow of underground water through sands at comparatively shallow depths. The method has been suggested as of possible use in detecting the movement of underground waters in oil fields, but it offers no promise of practical application for this purpose, as a brief description will show.

The essential features of the method are as follows: A 2-inch pipe, with the ordinary small drive point on the end, is driven or otherwise sunk to the shallow water sand under investigation. The drive point consists of a length of pipe 2 to 8 feet long, with a

⁵⁸ Slichter, C. S., Description of underflow meter used in measuring the velocity and direction of underground water, Water Supply Paper 110, U. S. Geol. Survey, 1905, pp. 17-31, or Slichter, C. S., Field measurements of the rate of movement of underground waters, Water Supply Paper 140, U. S. Geol. Survey, 1905, pp. 16-28.

funnel-shaped cast-steel drive shoe on one end and perforated above the drive shoe. The perforated section should be opposite the water sand. Sand and silt are kept out of the hole by use of screen wire and No. 20 to No. 30 gauzed strainer.

A number of these wells are placed in a group, one well being at the center and termed the central well, the others, termed radial wells, being at equal distances from the central well and preferably but not necessarily at equal distances from each other. The radial distance is about 4 feet and the radial wells 2 or 3 feet apart. Different radial and chord distances may be more applicable to special cases, but the variations from these distances ordinarily is not great.

The central well should be placed on the upstream side of the supposed flow, and the radial wells so sunk that the line through the central well and the middle well of the radial wells is parallel to the supposed direction of the underground flow.

The radial wells are equipped with "electrodes," which are polished metal rods approximately one-quarter inch in diameter and of about the same length as the drive point. A wooden plug or other insulating medium is fastened onto the bottom of the "electrode" to prevent contact with the 2-inch casing. A waterproofed insulated wire is soldered onto the top of the electrode, which is lowered to the bottom of the well by means of the wire. Wires are also soldered to the tops of the 2-inch casings of the central and radial wells. The wires attached to the casing and the wires attached to the electrodes are brought to a switchboard, which is provided with a sensitive ammeter of either the direct-reading or recording type and a suitable number of dry batteries. When the proper switches are closed the current generated by the batteries will flow underground from the casing of the central well to the casing of any radial well and back around to the central well through the electrical connections, thus completing the circuit. Suitable switchboard connections are also provided so that a current can be made to flow between the casing and electrode of each of the radial wells. The current is measured by the ammeter.

Before the test is started a suitable electrolyte (ammonium chloride, sodium chloride, or sodium hydroxide is commonly used) is placed in the central well by filling a perforated tube with the powdered or granular electrolyte, lowering the tube to the bottom of the well with as little agitation as possible, and leaving it there until the electrolyte has dissolved. This tube is removed from time to time and refilled with electrolyte to maintain the desired concentration in the well.

When there is a flow of water through the sand in which the well points are located, the dissolved electrolyte in the central well is

carried by the "underflow" in the direction of its flow and consequently toward one of the radial wells. An electrolyte dissolved in water increases the conductance of the solution, so that as the solution from the central well is carried toward a radial well more of the current will flow between the casings of the two wells.

After the electrolyte is placed in the central well, hourly or half-hourly readings of the current passing between the central well and the radial wells are taken. Before adding the electrolyte, ammeter readings are recorded for the central well to the casings of each radial well and for the electrodes in the radial wells to each of their casings.

As the electrolyte approaches a downstream well, the ammeter readings show a gradual increase, with a sudden and sharp rise when the electrolyte reaches the well.

The velocity of the underflow can be computed by dividing the distance between the central well and the well in which the electrolyte appears, by the length of time required for the electrolyte to travel from the former to the latter.

Slichter used 4 to 10 pounds of electrolyte in his tests, but the wells were shallow and close together. Much greater quantities must be used in other applications of this method where the underflow is slow or over great distances.

The possibility of applying this method or a modification of it to oil-field waters is remote, because the wells are spaced too far apart, are too deep, and the bulk of oil-field waters contain such high concentrations of salts that any small amount added could not be detected.

INDICATIONS OF A FIELD GOING TO WATER.

According to Lewis,⁵⁹ probably only 10 to 20 per cent of the oil underground is ordinarily recovered. Hence there is need of the operator delaying the oncoming of water as much as possible. Even if the production of a property is low, increases in price of oil and improved recovery methods may permit the future operation of properties that do not pay at present.

INCREASE IN WATER PRODUCTION.

The flooding of an area by top and bottom water can be prevented by correcting the offending wells when the trouble first starts. Therefore, the operator should investigate promptly any marked increase in the water content of a well.

The indications of a field "going to water" vary with each locality, but, of course, the most common and positive evidence is for the oil

⁵⁹ Lewis, J. O., Methods of increasing the recovery of oil from wells: Bull. 148, Bureau of Mines, 1917, p. 26.

wells to start producing water. When a group of wells located high up on the structure—for instance, on the top of a dome or on or near the top of a monocline—show water, while wells down slope do not, evidently some well or wells are at fault. When this happens, top or bottom water may be suspected, and the cause of its entering the wells may be improper depths of water shut off, leaky water strings, wells drilled into bottom water, or wells improperly plugged when abandoned.

When top water enters a field, it usually appears in wells scattered irregularly throughout the field; that is, one well may be making water while an adjoining well will be free from water. The same is true of bottom water. Usually troubles from top and bottom water are amenable to repair work on the wells. Water in the base of an oil sand and edge water present a much more serious problem, because the water when present in large volume will evidently advance wherever oil and gas are withdrawn.

Water in the base of an oil sand may show itself in abundant quantities, and as a rule careful plugging of the bottom of the hole with cement, in stages, will only retard the water. This is logical, because the plug only holds back the water until more oil is withdrawn, when the water rises above the top of the plug. (See pp. 146 to 148 and fig. 26.) The same remarks apply to the retarding of edge water. In areas where there happens to be a local impervious streak in the producing sand, either edge water or water in the base of an oil sand may be shut off in a well.

When the wells that are situated farthest down the slope along a line parallel in general to the underground contours show an increased water content, the encroachment of the edge water should be suspected; but, as previously shown, edge water may also occur up slope in unsuspected localities. (See figs. 21, 22, and pp. 84 to 86.)

INCREASE IN OIL PRODUCTION.

Frequently a sudden increase in oil production has been noticed in wells just before edge water appears. The hydrostatic head of the water as well as the pressure of gas is a factor in expelling the oil, particularly where the gas has been partly dissipated. Often encroaching edge water is preceded by a temporary increase in the oil output, owing to concentration of oil ahead of the water. Sudden unaccountable increases in oil production should be viewed with suspicion.

Figure 25 shows a remarkable increase in oil in a well just before the appearance of water. The oil production for November, 1911, was 3,210 barrels and for December 5,380 barrels, an increase of 2,170 barrels a month. The production for the eight months previous to the sudden increase in oil averaged 3,540 barrels per month,

and for the succeeding eight months 5,480 barrels, an average increase of 1,940 barrels per month; or the average daily production for the two periods was 118 and 182 barrels, respectively, showing an increase of 64 barrels per day. This increase in oil production

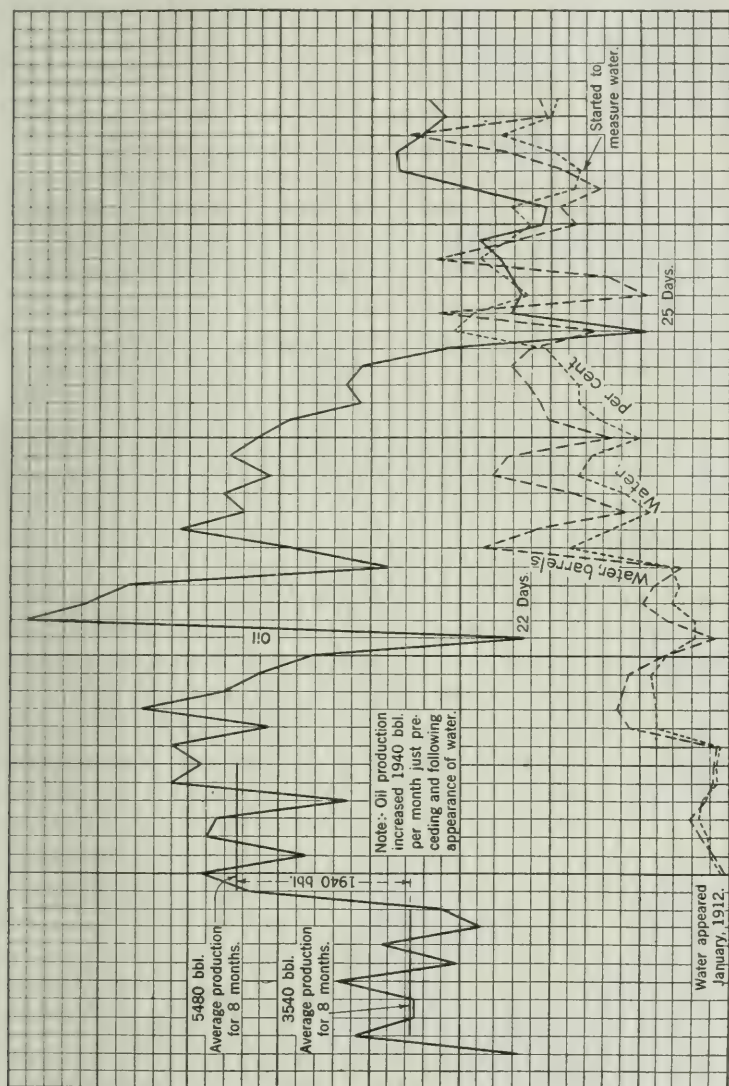


FIGURE 25.—Plot showing increase in oil production from well prior to encroachment of edge water.

preceded the appearance of the water by about six weeks, or at least that much time elapsed before the water began to attract special attention. This remarkable production of oil with much water continued for two years, but the proportion of water gradually increased until the oil production fell off rapidly.

At first the water content was determined by means of centrifuge tests, but in April, 1915, it was actually measured and the gaged results checked the centrifuge tests with surprising closeness. Such checking would be expected for a well producing a constant amount of oil and water, but for a well producing first oil and then water such close results could not be expected. The barrels of water were computed by means of the centrifuge percentages of water and the gaged oil production.

INCREASE IN TEMPERATURE OF FLUID.

In the Gulf Coast salt domes of Louisiana and Texas and in Mexico the temperature of the fluid commonly increases for several days prior to the well going to water, and operators recognize the significance of a relatively warm oil. As Deussen⁶⁰ says:

It is a matter of common knowledge to the experienced operators in the Gulf Coast field that a relatively warm oil indicates a close association with water. Also a fairly rapid increase in the temperature of oil is known to indicate the invasion of the well by water. This temperature change occurs over a period of several days and, when so increasing, is always considered to be an index of the fact that the well is going to water, an event which follows shortly afterwards.

Suman states:⁶¹

I have observed in the Humble field and at Saratoga that the temperature of the fluid increases very perceptibly as the well goes to water. * * * The highest temperature I have ever observed was in a well at Saratoga, at 1,500 feet depth, which was making about 90 per cent salt water, the temperature of this fluid was 115° F. I have heard men speak of higher temperatures than this, but upon questioning them closely they have always admitted that they did not measure the temperature with a thermometer but always estimated it.

I am unable to send you any information which will show the temperature of the fluid from a well for a certain period before and after the well goes to water.

De Golyer⁶² has made a study of the temperatures in the Mexican fields, and points out that the temperature of the water exceeds that of the overlying oil by several degrees, so an increase in temperature would naturally follow with the approach of water. His paper contains a description of the method of taking temperatures in wells. The method has also been described by Johnston and Adams.⁶³

The writer was unable to get figures showing a systematic report on the temperatures before and after the appearance of water in a

⁶⁰ Personal communication from Alexander Deussen, consulting geologist, Houston, Tex., Oct. 1, 1919.

⁶¹ Personal communication from John R. Suman, Rio Bravo Oil Co., Houston, Tex., Oct. 31, 1919.

⁶² De Golyer, E., The significance of certain Mexican oil-field temperatures: *Econ. Geol.*, vol. 13, June, 1918, pp. 275-301.

⁶³ Johnston, John, and Adams, L. H., On the measurement of temperatures in bore holes: *Econ. Geol.*, vol. 11, 1916, pp. 741-762.

well: De Golyer wrote several State geologists, but found they had no information on well temperatures.

From the data at hand, evidently the increase in temperature is noticeable only a few days before the water appears, hence temperature study does not seem particularly promising. However, so little systematic study has been done on oil-well temperatures it would seem worth while to take temperature readings on definite wells at certain specified times and in a uniform manner, so that the results could be compared. The production of oil and water by the well should be noted in conjunction with temperature studies.

A systematic study of temperatures of fluid would probably yield valuable results and perhaps establish facts that could be used in increasing the ultimate production of other wells. For example, if a well showed a relatively warm oil, the operator would realize he must not deepen the well and that he should produce slowly. If the well were allowed to flow wide open, the water in the base of the producing sand or limestone, being under a great head, would force itself to the bottom of the well and the water-oil contact would take a cone-like shape. If the well produced slowly, the water-oil contact would be more horizontal, thus permitting a greater ultimate recovery of oil.

USE OF PINS AND SYMBOLS.

In following on a map the water conditions, symbols and colored pins may be used to emphasize the water production of different wells. Triangular, square, circular, and other symbols may be used, each symbol designating a certain water content. The same use may be made of colored pins. For example, green could be used to indicate wells making 10 to 20 barrels of water daily; yellow, 20 to 50 barrels; and red, more than 50 barrels. If in such a system it were noticed that certain colored pins group themselves in certain localities, this might give some useful hint.

FIELD TESTS

In the study of water problems on an oil property, a series of field tests at wells making water and at drilling wells should be conducted. The water strings of oil wells making water may be tested; a reliable test should be made on the water strings of all drilling wells; bottoms of wells may be plugged where bottom water is suspected; and the sands of a drilling well should be tested. These tests are all limited by their cost and their practicability. Obviously, if a cable-tool well has been reduced to a 4-inch hole, a test should not be made at some depth where the 4-inch casing can not be freed later and carried to the depth where oil is expected. The suggestions

that follow may be used if conditions are favorable, but sound judgment is necessary. Rule of thumb suggestions must not be followed arbitrarily.

The same sand need not be tested in several wells, as one reliable test on a formation often suffices for a certain area. The necessity of knowing the former results of such tests emphasizes the value of good records.

TESTS FOR TOP WATER.

The production records will show that some wells have never made much water, some have made water from the time they were drilled in, and in others the water has appeared recently. Where a well has made water since its inception, the engineer should examine the histories to find how the original tests on the water string were made. If these tests are evidently inconclusive or unsatisfactory, new tests may be advisable. When a well suddenly shows a large amount of water, the water may have broken in from behind the pipe or the casing may have sprung a leak.

Before recommending a top-water test, the engineer should consider all the evidence at hand to determine whether possibly the water may be coming from another source—that is, it may be bottom water or edge water. Water coming around the water string often affects local areas only and may appear at any place on the structure. Furthermore, the well histories will indicate that at first only one well was affected, although the water may have worked later to neighboring wells.

In testing the water string of a producing oil well, the string should be tested first for a leak in the pipe; this may be done with a casing tester or swab bailer such as that described by Collom.⁶⁴

A bailer, or joint of old pipe closed at the bottom, is fitted at the top with a rubber gasket to fill the annular space between the bailer and casing. The fluid is bailed out of the well to a depth below that to be tested, then the casing tester is lowered into the well to that depth and left standing for a certain length of time. On account of the rubber gasket, any water that comes in above the tester will be caught and brought to surface in the bailer. Obviously, casing can be tested at any depth by this method.

Another method is to place a plug inside the casing near the shoe, bail the water down, and permit the well to stand several hours. Then the bailer is run to determine whether any water has come in.

Still another plan is to place a bridge several feet below the casing shoe, plug the hole from this point to a point 5 or 6 feet above the shoe, and make a bailing test. If the casing does not leak, this

⁶⁴ Collom, R. E., Casing leaks: Advance chapter, Fourth Annual Report, Calif. State Mining Bureau, May, 1919, pp. 8-11.

bridge may be drilled out to a depth 3 or 4 feet below the shoe, and the hole again bailed to determine whether water is coming in around the shoe. The most satisfactory plug is cement. The operator should be certain that the cement has set and that there is no chance of water coming up from the bottom.

TESTS FOR BOTTOM WATER.

In plugging the bottom of a well to test for bottom water the condition of the hole must be known. Old sidetracked casing, if present in the bottom, may permit the water to work up past the plug; often it is necessary to shoot and break up this old pipe. If a well is suspected of making bottom water, the bottom of the hole can be plugged in successive stages with cement until some definite information is gained regarding the source of the water.

A packer, lead plug, or seed bag should be used only for expediency, because they can not be depended upon to hold and should not be used for a permanent plug. If such a device happens to shut off the water the test is positive, but if the well still shows water the operator can not be sure that the plug is holding. With cement, on the other hand, the operator can feel much more certain of a successful job, provided the bailer shows the cement has set.

TESTS FOR INTERMEDIATE WATER.

In testing for intermediate water a bridge may be used to test the casing at any desired depth. For example, suppose that a sand midway between the cementing point and the bottom of the hole was suspected of making water. A bridge could be set in the sand suspected, the hole filled with cement to a point several feet above the sand, and a bailing or pumping test made. Very often a bridge saves a great deal of needless plugging.

In plugging up from the bottom to locate middle water the well should be plugged by stages; that is, one sand should be tested at a time.

Middle water can be located in a drilling well by testing successively each sand as drilling progresses.

TESTS FOR EDGE WATER.

The procedure in making a plugging test for edge water depends upon its location in the well—that is, when edge water occurs in the bottom sand, a plugging test similar to that for bottom water may be made; if the water is coming from an intermediate sand, tests similar to those for intermediate water may be tried. If edge water occurs in the only producing sand, then oil as well as water may be

shut off in a plugging job. Where the advance of edge water is gradual, it may be necessary to produce water with the oil as long as possible. In making a plugging test there is always hope, of course, of finding a local impervious stratum, and that by plugging to this stratum the water will be excluded from the well.

TESTS FOR WATER IN THE BASE OF AN OIL SAND.

The procedure employed in testing for water in the base of an oil sand is very similar to that used in testing for bottom water, although much greater care must be exercised, particularly in a shot hole. The well should be plugged with cement in successive stages in order to avoid shutting off the oil production. It may be necessary to add only 2 or 3 feet of cement each time. This is difficult to do, and the plug is often either too thick or too thin. When plugging in stages a hole where the water has not been shut off by the first attempt, it may be advisable to drill up several feet of the old plug to give "a better hold" and then replug to the desired depth. Before bailing out the water to test the job, sufficient time should be allowed for the cement to set. This is often indicated by whether or not the cement is hard. Different types of bottom hole plugs are on sale by oil well supply houses. Often these work satisfactorily.

TESTS ON DRILLING WELL.

The advantages of testing in a drilling well are many. All horizons suspected of bearing oil can be tested as drilling progresses. The tests will be governed by their cost and by the size of the hole. The most satisfactory way is to land the water string above the formation to be tested, because a large head of water in the hole may prevent oil showing. After the water string has been landed the casing should be tested to see that practically all water is excluded. Then drilling may proceed until a sand or other porous stratum is encountered, when a test can be made for oil. If the sand shows oil, a pumping test or bailing test lasting several days should be made in order to prove the productivity of the sand. Also a sample of the oil should be collected for analysis and the level of the fluid in the hole should be measured after the well has stood several hours. If the sand is barren, then drilling should proceed until another porous formation is found where a test can be made again. If water, not oil, is found, possibly the casing can be pulled and carried to a depth where it can be landed below the water sand.

Landing a string of casing to test every sand may not be practicable, because with running formations the pipe might freeze; this would necessitate the use of an extra string of casing, besides reduc-

ing the size of the hole. On the other hand, possibly the casing can be easily freed and carried deeper if the sand tested contains no oil. Often considerations of cost determine the frequency of the tests.

In drilling wells, samples of water from the different water sands can be collected for analysis, and the properties of the water from a certain sand definitely established. The fluid level can be obtained by allowing the well to stand.

In collecting samples of water, or in testing a sand for oil, the engineer should consider how much open hole is exposed to the test. If several sands are exposed the water may be coming from any one of these sands, and a large head of water from one sand may hold back oil in another from showing in the well.

Proper weight should be given to the location of the well before drawing any conclusions from the results of the tests. For instance, in a well down slope, the tests may prove it to be making water from a sand that farther up slope is producing oil. Such tests will aid materially in determining the edge-water line.

TESTS ON WATER STRING OF DRILLING WELL.

The water string of a drilling well should be carefully tested to determine whether it has satisfactorily shut off all water. In this work exact measurements are necessary, because a difference of a few feet in the landing depth of the pipe may be an important factor. Before landing or cementing the water string, measurements should be taken of the depth of the hole and of the total length of the casing. In rotary wells it is advisable to recheck the length of the drill pipe by accurately measuring each stand with a steel tape; also careful measurements should be taken of any formation that may serve as a marker.

MEASUREMENTS.

The depth of a well drilled by standard cable tools may be measured by "stringing in" the bailer on the sand line over the derrick, or by stringing in the drilling cable⁶⁵ in the same way. The depth of a rotary drilled well may be determined by measuring the stands of drillpipe. Careful sand line measurements can be obtained which are correct within a foot. The distance over the derrick should be measured with a steel tape, for a cloth tape or metallic tape is apt to stretch and give incorrect measurements. In measuring stands of drill pipe, the measurement should be from the face of the box on the top joint to the face of the tool joint on the lower end of the

⁶⁵ See Bowman, Isaiah, Well-drilling methods: Water Supply Paper 257, U. S. Geol. Survey, 1911, p. 125.

stand. Each new joint added to the drill pipe should be measured with a steel line as it is put in. The time for observing most care in the measurements is when the drill nears the landing point for the casing.

Companies have purchased long steel tapes ranging up to 3,000 feet in length to measure the depth of the hole. A weight of about 5 or 10 pounds, depending on the depth of hole, is attached to the bottom of the steel line. By the "feel" of the line the drillers can determine when the weight is resting on bottom. The writer's experience has been that careful "stringing in" of the sand line in a cable tool well and measuring in of the stands of drill pipe in a rotary hole gives as satisfactory results, and in some wells more so, than the long steel tape. This is particularly true of deep wells filled with fluid, as the "pick up" of the tape is hard to determine; also any magnetized condition of a long string of pipe may hold a steel tape to the side of the casing, which makes an accurate measurement very difficult.

The California State Mining Bureau⁶⁶ has carefully considered the matter of measuring the depth of a drilling well, and its suggestions are quoted:

Methods of measuring the depth of oil wells and the amount of casing put into them are of extreme importance in order that water shall be shut off at the proper depth and casing perforated between the proper depths. While the matter may appear of slight importance to some careful operators, it has been found that gross errors are frequent enough to justify some general regulations.

1. All measurements must be made with a steel tape. Cloth or metallic tapes can not be depended upon, as they are subject to great change in length. A 5-foot stick used on a sand or drilling line, for distances more than 200 feet, is inaccurate. The reasons for such inaccuracy are that exact markings on the line at the ends of the stick are difficult to make and their great number quickly multiplies the error.

2. The depth of the well shall in all cases be determined by running a bailer or string of tools to the bottom. The unit of measurement, when cable tools are used, shall be the distance from the floor of the derrick along the sand line over to a point level with the top of the flanges of the reel. This is commonly known as the distance the derrick "measures over," and details for such measurement are stated below. If measurement is on the drilling line, it shall be from the floor over to a point near the bull wheel and 5 feet above the floor, as determined by setting up a 5-foot stick.

The depth of a rotary hole before casing is put in shall be determined by measuring each stand of drill pipe with steel tape, measurements to be from top of tool-box joint to bottom of shoulder on tool-joint pin.

3. The length of a string of casing shall, when considered necessary by the supervisor or deputy, be determined by measuring to the shoe of the casing from the derrick floor. This measurement can be made on the drilling line

⁶⁶ Second Annual Report of the State Oil and Gas Supervisor, 1916-17; California State Min. Bureau, Bull. 82, 1918, pp. 59-61.

by using an underreamer, a latch jack, or any other tool which definitely locates the shoe of the casing.

4. A derrick should be "measured over" immediately before it is intended to measure the depth of well or of casing. A measurement made when the rig is new may not be correct after the rig and rig irons have been in use for some time.

The "distance over" can be determined in the following manner, using a bailer and sand line:

(a) Run the bailer into the well a short distance and tie a string on the sand line level with the surface of the floor, using a straightedge or steel square to determine the correct position.

(b) Tie a strand of rope (target) tightly on the sand line at a position on a level with the top of sand-reel flanges, laying a straight stick on top of the flanges to determine this position.

(c) Lower the bailer into the well until the target is within easy reach from the derrick floor. Attach the end of a steel tape to the sand line at the target. Raise the bailer until another target can be fastened at the end of the tape and tie another target. Lower the bailer, detach tape, hoist bailer and attach tape at the second target, hoist bailer and set a third target. Repeat the operation until it is possible to measure with the tape to the target first set at the floor. The tape must be shorter than the height of the derrick so that it will not go over the pulley at the crown block.

When a target is tied to the line, paint should be put on the line above and below the target to show any displacement of the target.

To measure into the well after the unit length or "distance over" is determined hold the bottom of the bailer dart, when raised, level with the surface of the floor, set a target at the top of the flanges of the reel, lower the bailer until the target is level with the floor, and set a second target at the reel. Correct count of the targets is most easily kept by detaching and keeping each one as it reaches the floor.

The depth can also be conveniently measured when the bailer is pulled out of the well by setting the first target even with the floor while the bailer is on bottom, hoisting until the target reaches the flanges of the reel, set new targets at floor level, and remove old ones as they reach the reel.

BAILING TESTS.

The water string of a drilling well should be carefully tested after it has been landed or cemented. The time allowed for ordinary cement to set should not be less than two weeks.⁶⁷ The most positive test of a water string is to drill a pocket 4 or 5 feet below the bottom of the casing shoe and then bail the hole dry. However, it is not always safe to bail a hole dry, because the operator must be certain that he does not bail the water below a depth where the column of water behind the casing will have sufficient pressure to collapse the pipe. Casing is much weaker when it is slightly flattened or dented. Table 3, following, gives the water column, using a safety factor of 2, that will collapse various sizes of casing. If the water level outside of the casing stands near the surface, these figures represent the

⁶⁷ For a description of cementing water strings, see Tough, F. B., *Methods of shutting off water in oil and gas wells*: Bull. 163, Bureau of Mines, 1918, p. 51.

maximum depths to which the well can be bailed with safety. The use of casing strong enough to permit a well being bailed dry is preferable, but when this is not possible the operator may bail the fluid to a certain level and let the well stand several hours. This level should be lower than the head of water on the outside of the casing, so that if the pipe leaks the change of fluid level will be readily detected.

TABLE 3.—*Collapsing pressures and capacities per linear foot of lapwelded steel casing of sizes commonly used in California.*^a

Size.	Weight per foot.	Outside diameter.	Inside diameter.	Thick-ness.	Collaps-ing pressure per square inch.	Equiv-alent water column.	Water column with safety factor of 2.	Capacity per linear foot.	
<i>Inches.</i>	<i>Pounds.</i>	<i>Inches.</i>	<i>Inches.</i>	<i>Inches.</i>	<i>Pounds.</i>	<i>Feet.</i>	<i>Feet.</i>	<i>U. S. gallons.^b</i>	<i>Cubic feet.</i>
4 $\frac{1}{2}$	16	4.750	4.082	0.334	4,710	10,850	5,425	0.6792	0.0908
4 $\frac{1}{2}$	12.85	5.000	4.506	.247	2,900	6,680	3,340	.8281	.1107
4 $\frac{1}{2}$	15	5.000	4.424	.288	3,610	8,320	4,160	.7982	.1067
5 $\frac{1}{8}$	20	6.000	5.352	.324	3,290	7,580	3,790	1.1677	.1561
6 $\frac{1}{8}$	20	6.625	6.049	.288	2,380	5,480	2,740	1.4916	.1994
6 $\frac{1}{8}$	24	6.625	5.921	.352	3,220	7,420	3,710	1.4295	.1911
6 $\frac{1}{8}$	26	6.625	5.855	.385	3,650	8,410	4,205	1.3974	.1868
6 $\frac{1}{8}$	28	6.625	5.791	.417	4,070	9,380	4,690	1.3667	.1827
6 $\frac{3}{8}$	20	7.000	6.456	.272	1,980	4,560	2,280	1.6988	.2271
6 $\frac{3}{8}$	26	7.000	6.276	.362	3,100	7,140	3,570	1.6061	.2147
6 $\frac{3}{8}$	28	7.000	6.214	.393	3,480	8,020	4,010	1.5739	.2104
6 $\frac{3}{8}$	30	7.000	6.154	.423	3,850	8,870	4,435	1.5440	.2064
7 $\frac{3}{8}$	26	8.000	7.386	.307	1,940	4,470	2,235	2.2240	.2973
7 $\frac{3}{8}$	28	8.625	8.017	.304	1,670	3,850	1,925	2.6204	.3503
7 $\frac{3}{8}$	32	8.625	7.921	.352	2,150	4,950	2,475	2.5583	.3420
7 $\frac{3}{8}$	36	8.625	7.825	.400	2,630	6,060	3,030	2.4962	.3337
8 $\frac{1}{2}$	38	8.625	7.775	.425	2,880	6,640	3,320	2.4648	.3295
8 $\frac{1}{2}$	43	8.625	7.651	.487	3,510	8,090	4,045	2.3863	.3190
9 $\frac{1}{2}$	33	10.000	9.384	.308	1,280	2,950	1,475	3.5899	.4799
10 $\frac{1}{2}$	40	10.750	10.054	.348	1,420	3,270	1,635	4.1210	.5509
10	45	10.750	9.960	.395	1,800	4,150	2,075	4.0440	.5406
10	48	10.750	9.902	.424	2,030	4,680	2,340	3.9976	.5344
10	54	10.750	9.784	.483	2,510	5,780	2,890	3.9026	.5217
11	47	11.750	11.000	.375	1,380	3,180	1,590	4.9334	.6595
11	60	11.750	10.772	.489	2,220	5,120	2,560	4.7307	.6324
11 $\frac{1}{2}$	40	12.000	11.384	.308	840	1,940	970	5.2827	.7062
12 $\frac{1}{2}$	40	13.000	12.438	.281	500	1,150	575	6.3083	.8433
12 $\frac{1}{2}$	45	13.000	12.360	.320	750	1,730	865	6.2298	.8328
12 $\frac{1}{2}$	50	13.000	12.282	.359	1,010	2,330	1,165	6.1497	.8221
12 $\frac{1}{2}$	54	13.000	12.220	.390	1,210	2,790	1,395	6.0869	.8137
13 $\frac{1}{2}$	50	14.000	13.344	.328	640	1,470	735	7.2598	.9705
13 $\frac{1}{2}$	70	16.000	15.198	.401	790	1,820	910	9.4150	1.2586

^a Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163, Bureau of Mines, 1918, p. 20.

^b Figures in this column determined by multiplying corresponding values in cubic feet by 7.4805.

After a pocket is drilled below the casing shoe, and the water is bailed out for a test, the operator must remember that a certain amount will have splashed onto the inside of the casing. After a few hours, several feet may have drained back from the side of the casing into the hole. This must be allowed for in testing a water string.

Occasionally, when a 4 or 5 foot pocket is drilled below the casing shoe, the operator will unexpectedly encounter an oil sand. The oil may come into the hole rapidly. If the presence of this oil necessitates bailing to a certain level, all water should be bailed from the bottom of the hole—provided this will not collapse the casing—and the fluid level of the oil measured. A centrifuge test may be taken of the oil near bottom. After the well has stood several hours, the bailer can be run to determine the top of the oil, and then run at successive depths to determine whether any water has come in. Where no increase in water is noted, another centrifuge test may be taken of the oil to determine whether the proportion of water in suspension has increased appreciably.

The California State Mining Bureau⁶⁸ prepared a set of instructions to the operators when testing water strings. These cover the subject fully and are quoted below:

1. Measurements to the bottom of the hole and to the bottom of the casing shoe must both be carefully checked before the casing is landed or cemented and before notifying the deputy supervisor of intention to test. A steel tape should be used in determining the distance that the sand line or drilling line "measures over."

2. Casing must be tested by bailing the well to a safe depth (see collapsing strength of casing, Table 3) before drilling below the shoe. Old casing may collapse with less pressure than that indicated for new casing. Testing by applying pump pressure inside the casing will not always reveal leaks.

3. Drilling out of cement or other material in the casing must be carefully done to avoid damage to the shut-off. The drill must merely be run far enough to go entirely through the cement and below the shoe. A distance of 5 to 10 feet below the shoe should be ample. By drilling too far below the shoe complications may arise which will prevent a positive test.

4. Bailing should, if possible, continue until all fluid is removed from the hole, unless there is danger of collapsing the casing. It is advisable to run the bailer until it brings up nothing but mud on the last run, then allow the well to stand an hour or more and again bail to remove water which has sprayed into the inside of the casing and drained down. When a well is in such condition that it can not be safely bailed dry, the fluid should be lowered to a certain depth by continuously running the bailer to that depth until no more fluid is brought up. A permanent target should be placed on the line to mark the bailing point. If both oil and water are present in a well, which can not be bailed dry, it may be necessary to remove the water by continuously bailing it from the bottom of the well until the bailer fails to bring up water. The well should be allowed to stand several hours and the bailer run to increasing depths to determine the point where it again picks up water. At this point the well is ready for inspection by the deputy supervisor and afterwards the water may again be removed by bailing from the bottom of the well, account being kept of the amount bailed out. It may be necessary to repeat this process several times in order to determine whether the water is

⁶⁸ Second Annual Report of the State Oil and Gas Supervisor of California, 1916-17: Calif. State Min. Bureau, Bull. 82, 1918, pp. 57-58.

being exhausted. In case of high pressure and flow of gas, or in case of heaving formation, it will probably be possible to test the well only by pumping.

5. When a tight or closed bailer is used in a deep well, some sort of outlet or valve should be provided in order to relieve the pressure, which may endanger the lives of persons in the derrick when the bailer comes out of the well.

A leaky bailer should not be used in testing.

6. A well must stand at least 12 hours without any bailing whatever, before it is to be witnessed by a representative of the bureau, and a longer time⁶⁹ is preferable.

7. * * * A proper test to determine whether or not a sand carries oil or water can not be made unless water from all other possible sources is absolutely excluded.

DETERMINATION OF THE SOURCE OF WATER IN OIL WELLS.

The subject of determining the source of water in oil wells has been discussed by the writer in a recent paper.⁶⁹

The determination of the source of water in an individual oil well or a group of oil wells of a large producing property requires a careful study of most of the data outlined on pages 11 to 15, together with a series of field tests, discussed on pages 125 to 134.

The problem should be attacked from two sides—a study of office data and field tests. This work should be carried on together. The results of the office work may determine the source of the water, and at any rate will likely suggest field tests which will afford valuable information. Prior to making any field tests the engineer should discuss with the foreman the conclusions reached in the study of the data.

NEED OF GOOD RECORDS.

It is evident that the determination of the source of water in a field is dependent upon accurate and complete records. With such records the problem can generally be solved, but without them the solution is much more difficult. However, in all fields there are records, some complete, others incomplete, from which an idea can be gained of the wells' history. The available information should be compiled in logical form, the problem studied, and as suggestions arise they should be tested and checked by mechanical and field tests on the wells.

Much of the necessary information can be gained from drilling wells and much from producing wells. Before attempting corrective measures that involve considerable expense, it is advisable first to learn as much as possible from the data available. This is best covered by a systematic study of the wells and their histories.

⁶⁹ Ambrose, A. W., Analysis of oil-field water problems: Bull. Am. Inst. Min. and Met. Eng., September, 1920, 21 pp.

USE OF DATA.

The data needed generally include well logs with detailed histories (see pp. 11 to 15), field maps showing well elevations and locations (see pp. 9 to 11), correlated cross sections (see pp. 38 to 44), underground structure contour maps (see pp. 46 to 49), often peg models (see pp. 52 to 55), individual well production records (see pp. 58 to 62), and water analyses (see pp. 88 to 90). The above data should be prepared at the start in the general order mentioned. Other miscellaneous graphic charts and data can be prepared as the work progresses.

The history and production data of each well should have been worked up and arranged in systematic form for ready reference. With the correlated cross sections before him, the engineer can make a detailed study of each well and a tabulation can be prepared showing (1) the distance between the marker and the bottom of the hole; (2) the distance between the marker and the bottom of the water string; (3) the distance between the marker and the top of the plug; (4) the water production before and after the plug was put in; (5) the water production before and after any deepening job; (6) the initial and present production in oil and water; (7) date at which the well first started to make a serious amount of water; (8) remarks as to what any field tests showed; and (9) the source of the water according to the analysis, etc. All of this information may be tabulated under each well on the cross sections, or, where there are many wells to investigate, may be tabulated on a separate sheet.

The engineer should review these data broadly, considering the field as a whole, to see whether the water is troublesome locally, or whether it represents a widespread invasion over a large area.

MODE OF IDENTIFYING SOURCES OF WATER IN OIL WELLS.

In most fields water may be coming into the well from one of several sands or from more than one sand. Evidently no definite line of attack can be outlined for determining the source of the water in every well. Each well presents a separate problem which must be worked out independently of any other well, but certain fundamental considerations are involved. These are outlined in the following discussion.

The procedure in determining the actual source of the water in a particular well has been aptly stated by Tough,⁷⁰ as follows:

⁷⁰ Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163, Bureau of Mines, 1918, p. 15.

"All possible sources must usually be considered and checked off by elimination until the problem is solved."

Some of the questions that arise in the study of the source of water are: Is it entering a group of wells down the dip of the formation? If so, this might indicate edge water, although the water may be coming from bottom or top; and then the question arises, Are the wells cemented too high or are they drilled too deep? Did water first appear in one well and then show later in adjoining wells? If so, one well may be at fault and let water into the oil sands from which it works through to adjoining wells. Is the well high up on the slope and is it drilled too deeply or the water shut off at too high a point? Thus the relative location of the wells on the structure making water should be considered.

The production records indicate, of course, which wells are making large amounts of water, and complete records show when and where the water first appeared. The first appearance of the water is essentially important, and any work being done on wells in the neighborhood, such as swabbing, shooting, or deepening, should be investigated.

Fluid-level records (see pp. 193 to 197) may indicate what well is causing trouble. The history of an abandoned well near by may indicate that the well was not properly plugged upon abandonment and that the water trouble started shortly after, the abandoned well presumably being at fault. It may be found that water appeared at the completion of a well in which the water string is landed too low, and that this well let water into the oil sands. Where mud-laden fluid or cement is used behind the water string there is much less likelihood of such trouble.

An analysis (see pp. 88 to 90) of the water may promptly indicate its source. Has a dye or other detector (see pp. 106 to 125) been used to trace the water, and if so what were the results? Has any field test been made on the different water strings of "wet" wells, and, if so, what were the results? These factors indicate certain general considerations to be used in studying the source of the water.

TOP WATER.

The question of whether a well is making top water should be considered from two angles—whether the water string leaks, and whether the casing shoe has been landed too high. (See p. 161.) The casing may leak or the water may be coming around the casing shoe. The history will show whether the well made water when first drilled in or started to make water later, also any bailing tests made at the time the water string was landed. If the original tests were satisfactory the probabilities are that water has not broken

in. Some operators in the Mid-Continent field put Venetian red behind the casing so that water breaking in will be indicated by the color of the fluid. If no tests are recorded and no information can be obtained from the field men, a test of the water string might be advisable. This can be done (see field tests for top water, pp. 126 and 127) by setting a plug in the casing shoe to test the casing, or a plug can be set several feet below the shoe and the water bailed down to learn whether it is coming in around the shoe.

In looking for top water the engineer should first select a well in which the water string is landed highest stratigraphically but still makes no water. After the proper depth for landing water strings has been determined, this distance should be expressed in reference to the marker. Then a comparison of cross sections and tabulations will readily show whether the shut-off point in any well is too high.

BOTTOM WATER.⁷¹

If all data and tests indicate that the well is not making top water, the possibilities of bottom water being the source should be considered, or this study can even be made in conjunction with the top-water study. Then the question arises, "Has the well been drilled too deeply, as indicated by the tabulation showing the safe point to which wells may be drilled without encountering bottom water?" The well that is drilled deepest stratigraphically but still makes no water determines the maximum depth below the marker to which a well can be drilled with safety. The value of this figure is sometimes lessened by irregularities in the water levels.

Plugging jobs also give information on bottom water. If the well has been plugged, the engineer should review any tests made afterwards for evidence as to whether the plug was tight. If bottom water is suspected and has not been plugged off, the well may be tested by plugging, preferably with cement. Bottom water may be indicated by deepening jobs recorded in the history. For example, a record showing that a well made no water until deepened or shot, after which there was a marked inflow in water, would indicate that the bottom water had been encountered. As stated on a preceding page (p. 95), bottom water usually has distinct chemical properties.

INTERMEDIATE WATER.⁷²

When all the information indicates that the water is not top or bottom water, it may be coming from an intermediate stratum. This is a difficult matter to determine, and before making a decision one should weigh carefully the probabilities of top and bottom water.

⁷¹ For field tests of bottom water, see p. 127.

⁷² For field tests of intermediate waters, see p. 127.

If the water string is landed low enough and the original bailing tests indicate a tight job, and furthermore, if the well is not drilled deeply enough for bottom water, then the water is likely coming from an intermediate water sand, or possibly through the oil sand from another well.

The histories of adjacent wells should be noted to learn whether these wells have a similar water and whether the bottoms of any of them have been plugged. If a plug was properly placed in a hole and held back any bottom water, but the well still made water, this may be coming from a sand higher up. In looking for evidence of intermediate waters, the engineer may find that adjoining wells were deepened in successive stages and that their histories indicate the depth below the marker at which an intermediate water is found.

The middle water often has distinctive properties different from those of the top and bottom waters, and these differences are brought out by water analyses.

The engineer must always keep in mind that the plug or casing seat, though tight at first, may later fail. However, such failure is not particularly common. Swabbing and shooting may also cause failures.

EDGE WATER.⁷³

Edge water may be suspected when a group of wells down slope show increased oil production not otherwise accounted for. (See fig. 25 and pp. 122 to 124.) Again, a group of wells located roughly parallel to a structure contour may show a sudden increase of water. Perhaps wells are producing oil from a sand in one locality, whereas in wells down slope this sand contains water; somewhere between is the edge-water line, and in time the water will probably advance to the oil wells. Two fundamental ways of proving edge water are as follows:

(1) Positive correlation of a sand carrying oil in places up the dip and water in places down the dip;

(2) Definite knowledge, by elimination of all other possible sources, that a well once producing oil from a given steeply tilted sand is now producing water from that sand. Even then a neighboring well may have let the water into the oil sand.

An interesting study in edge-water encroachment is the rate of travel of the water; that is, the number of feet it travels each year.

WATER IN THE BASE OF AN OIL SAND.⁷⁴

The well may perhaps be making water from the base of an oil sand. This might be indicated by an analysis, revealing that the water was different from any waters formerly noted in the well.

⁷³ For field tests of edge water, see p. 127.

⁷⁴ For field tests for water in the base of an oil sand, see p. 128.

Where water is present in the base of the oil sand, the wells usually turn from oil to water very suddenly. If the well is a large producer it shows little evidence of gas, and flows evenly as though under hydrostatic pressure. The depth of the well below the marker will indicate whether it is deep enough stratigraphically to reach a lower water. (See discussion on "Bottom water," p. 81.)

In a decidedly lenticular structure, water may occur in any part of the hole and the same water is often referred to and tested as top, bottom, or intermediate water, according to its depth in the wells.

CORRECTION OF WELLS MAKING WATER.

The previous discussion has shown that top, bottom, or intermediate water, edge water, and water in the base of an oil sand may afford water to a producing oil well.

This part of the bulletin briefly discusses repair work on a well after the source of the water entering has been determined. No attempt is made to describe the actual mechanical details in such work. Valuable information on repair work and proper methods for excluding water from oil and gas wells has been given in other publications⁷⁵ of the Bureau of Mines.

Each well is a separate problem, but the following generalities may be useful:

Early in the work the operator will undoubtedly reach conclusions as to the source of the water in certain wells; these should be repaired without further delay. In correcting water troubles in a field the first work is to take immediate care of those wells where the source of the water is definitely known, and the wells corrected first should be those surrounded by producing oil wells and those suspected of doing most damage to the field.

When a well makes large quantities of water the operator should repair it rather than try to lift the water by compressed air (see pp 75 to 78) or huge pumps. Actual experience has shown time and again that in general the operator should not try to pump the water from a sand, but rather do repair work on the wells.

In using cement the hole should be free from oil. Cement will set in most types of water, but various operators are satisfied that it does not set well in the presence of oil. The oil can be removed by flushing the hole with water. Probably a much more important factor in preventing the setting of cement is agitation from inflowing

⁷⁵ Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163, 1918, 118 pp.; Lewis, J. O., and McMurray, W. F., The use of mud-laden fluid in oil and gas wells: Bull. 134, 1916, 86 pp.; Pollard, J. A., and Heggem, A. G., Mud-laden fluid applied to well drilling: Tech. Paper 66, 1914, 21 pp.; Heggem, A. G., and Pollard, J. A., Drilling wells in Oklahoma by the mud-laden fluid method: Tech. Paper 68, 1914, 27 pp.; McMurray, W. F., and Lewis, J. O., Underground wastes in oil and gas fields and methods of prevention: Tech. Paper 130, 1916, 28 pp.

gas or water. This can be overcome by keeping a head of water in the well to hold back the gas or underground water.

TOP WATER.

Top water (see pp. 79 to 81) may gain access to the oil sands by (1) a leaky water string, either through a leak in the pipe or by water working down around the outside of the casing shoe; or (2) the water string may be landed above the bottom of a water sand, or an oil or gas sand may have been flooded by a neighboring well.

An attempt to repair a leaky water string in a producing oil well with a packer or other inexpensive means is permissible, but in a new well the water string should properly exclude the top waters before the well is drilled into the oil sand. Perhaps the casing can be pulled and defective joints replaced, but even if the landing of another water string is necessary, the operator should not drill into the oil sand until the top water has been permanently shut off.

USE OF PACKER TO REPAIR LEAK IN WATER STRING.

For stopping a leak in the casing, regardless of its cause, one remedy is to place a packer between the tubing and the water string. (See discussion on pp. 79 to 81 and fig. 18.) Before the packer can be placed it may be necessary to cut off the oil string, if it is complete, leaving only a liner. Where the water string leaked above the casing shoe in certain wells, a string of casing with a packer on the bottom has been hung inside the water string to shut off the water, the packer filling the annular space between the two strings. This practice is quite common in the eastern fields.

SCREWING CASING TOGETHER TO SHUT OFF TOP WATER.

A water string may leak because it was not screwed together properly when put in the well. Collom⁷⁶ cites two instances of the casing in a well screwed up, and in one 10½ inches and in another 26 inches, thus shutting off large leaks in the pipe. Collom⁷⁷ also says a company screwed the casing together 30 inches and shut off the water.

DRIVING WATER STRING TO SHUT OFF TOP WATER.

Top water occasionally works down into the underlying oil and gas sands around the outside of the water string, or it may be coming from a sand directly below the casing shoe. Where there are sev-

⁷⁶ Collom, R. E., Comparison of various methods of excluding water from oil wells in California: Bull. 84, California State Mining Bureau, 1917-18, pp. 136-137.

⁷⁷ Collom, R. E., Casing leaks: Advance chapter, Fourth Annual Report, California State Mining Bureau, May, 1919, p. 11.

eral feet of shale or clay or a hard shell below the bottom of the water string and above the oil sand the casing can often be driven a few feet, thus shutting off top water. A good casing shoe on the water string will insure more chance of success. In fact, every water string landed should have a strong casing shoe on bottom. Driving the water string is worthy of trial, particularly if a formation below will serve as a good seat.

If the hole stands up so well that the casing can be pulled, the casing may be pulled and run back with a better and bigger casing shoe that can be driven. After the pipe is replaced in the hole, it should preferably be cemented. In fact, if the casing seems to be poorly seated and the pipe is loose, the best way is to set a bridge above the oil sand, but below the casing shoe, and force cement behind the pipe.

FORCING CEMENT BEHIND PIPE TO SHUT OFF TOP WATER.

Collapse of the water string is usually detected when the tools, bailer, or tubing are run into the hole. Collapsed casing should be swaged out, if possible, but repairing a leak caused by collapsed pipe is usually difficult. Sometimes a packer may be used or cement may be forced through the crack into the space behind the pipe, but often another water string must be landed, especially in a drilling well. In an old well redrilling may be necessary.

A leak in the casing may perhaps be due to a split joint, to the pipe being eaten through by corrosive waters, to shooting, or possibly to line wear. If the opening is large, a bridge may be placed in the pipe, capped with a cement plug, and cement forced through the leak. If the opening is small, the casing may be ripped and cement forced in behind the pipe. This has worked successfully in several wells.⁷⁸ The method of forcing cement through a hole in the pipe is similar to that of forcing cement behind the water string when a bridge is placed below the casing shoe, as described below. If the pipe can not be moved or moving is not advisable, possibly a bridge⁷⁹ can be placed several feet below the shoe of the water string. The bridge should be capped with cement to within 2 or 3 feet of the bottom of the shoe.

After the cement has set for several days the bailer can be run to determine its hardness. If the cement has set, then tubing can be placed in the well 10 to 15 feet off bottom, and an effort made to obtain circulation between the outside of the casing and the wall of the hole. Sometimes a packer is placed near the bottom of the tubing to fill the annular space between the tubing and the casing,

⁷⁸ Collom, R. E., Casing leaks: Advance chapter, Fourth Annual Report, Calif. State Min. Bureau, May, 1919, p. 11.

⁷⁹ Bridges are made of rock, cement, brick, sacks, or occasionally a wood plug is used.

but a tight head is preferable to a packer. A tight head is placed at the top of the casing, sealing the space between it and the tubing. Then water or mud may be pumped in under a pressure of several hundred pounds to show whether circulation can be obtained. If circulation is possible, cement may be pumped in⁸⁰ behind the pipe as described by Tough.⁸¹ The pressure should be held for two or more days in order to allow the cement to set.

With free circulation the Perkins process⁸² without any tubing may be used.

If circulation can not be obtained cement may perhaps be forced into the formation. If water can not be forced in and the pumps stop no effort of course should be made to pump in cement. Cement will not go behind the pipe if water will not.

The use of a packer is objectionable because when the pumps stop, as may happen from excessive rise of pressure caused by poor circulation, the tubing can not be quickly freed of any cement in it. Where a tight head is used, a valve can be opened at the surface and enough water pumped in through the tubing to flush out the cement in the tubing and that between the tubing and the casing.

In general, the tubing method is somewhat objectionable because if an accident happens all the cement may not be pumped out of the tubing, and some of it may set inside the tubing, making an awkward and expensive fishing job, especially if the packer happens to stick near bottom. Furthermore, where the tubing must be pulled immediately, pressure can not be maintained and cement behind the pipe may run back into the well. A 6-inch nipple with left-hand thread may be placed above the packer so that the tubing can be unscrewed and pulled if the packer sticks. This leaves only the packer to fish out or drill up. Obviously the tight head is preferable to the packer.

USE OF LINER TO SHUT OFF TOP WATER.

If the water string is landed several feet too high, it may result in a water sand directly below the casing shoe. The same condition results when edge water approaches in the sand directly below the casing shoe or when an upper oil sand has been flooded by a neighboring well.

A liner has been set, surrounded by cement, to shut off this water. First a bridge is placed in the hole at the proper depth below the

⁸⁰ Collom points out (in Bulletin 84, California State Mining Bureau, p. 142) that "re-cementing through tubing is apparently not an efficient one (method) * * * Of 17 jobs of re-cementing through tubing, under pressures varying from 500 to 1,275 pounds per square inch, only one was successful."

⁸¹ Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163, Bureau of Mines, 1918, pp. 32-42.

⁸² Tough, F. B., Work cited, pp. 43-50.

water string, this depth depending on the location of the next producing oil sand. After the hole has been flushed with water, enough cement, by estimate, to fill the annular space between the sides of the hole and the liner is dumped on the bridge or the bottom of the hole. The liner, closed at the lower end with a wooden plug, is lowered into the hole and forced to bottom. The cement rises outside the liner and fills the space between it and the wall of the hole. Any cement that comes over the top into the liner is bailed out. As a rule several joints of pipe, enough to extend up into the water string, are used in such a trial. This method may be successful in many wells, but where the water is under strong hydrostatic pressure the cement might not hold it back after the fluid level in the well is lowered. The work must be done rapidly so that the initial set of the cement does not start prior to placing the liner.

REDRILLING OR LANDING A NEW STRING OF PIPE TO SHUT OFF UPPER WATER.

When the water string has been cemented too high, another string of casing may be needed to make a shut-off below the old one. Often some old pipe can be cut and recovered for this use. The solution of the problem depends entirely on the condition of the hole. If the water string is of small size the well may have to be redrilled. However, in a well where either $6\frac{5}{8}$ -inch, $8\frac{1}{4}$ -inch, or 10-inch casing is used for the water string, usually the next smaller size pipe can be cemented at a lower depth in an impervious stratum.

Oftentimes top water leaking around the casing can be shut off by redrilling the well and landing a smaller size string at a greater depth, provided the oil sand is not too close. If the old casing has been landed only a few feet above the oil sand, it may be necessary to set a bridge just above the oil sand, shoot the bottom of the casing, and recement at the same depth or at a point deep enough to exclude top water. The character of the formations often governs this depth. In such work, all of the old casing possible should be recovered.

Considerable trouble and cost may be experienced when the water sand lies only a few feet above the oil sand and a few feet below the casing shoe, for then the shutting off of water under a high head is difficult.

BOTTOM WATER.

In a well where the water is known to be coming from bottom, careful plugging with cement is recommended.⁸³ If the operator does not know which sand at the bottom carries water, the well should be plugged in stages, one sand at a time, and each plug care-

⁸³ For methods of introducing cement into the bottom of well, see Tough, F. B., *Methods of shutting off water in oil and gas wells*: Bull. 163, Bureau of Mines, 1918, pp. 82-85.

fully tested to note the results. If the well has an oil string or liner in the bottom, the best plan is to rip or shoot this pipe before placing the cement. (See fig. 22 and discussion on pp. 86 and 87.)

Mud-laden fluid has been used to shut off bottom water,⁸⁴ but after the well has been bailed out and pumping started, the pressure of the water may overcome the resistance of the mudded barrier and the pressure of the oil column in the hole, and the water may start working back into the hole. Once the water reaches the well, the old water-flow channels will be reestablished in a short time.

In general the use of lead plugs, lead wool, or packers in the bottom of a hole is not recommended, although certain wells have been benefited by their use. Among the latter may be mentioned a well in the Mid-Continent district. Cement placed in the well would not set because of the agitation caused by the bottom water flowing from under a limestone shell about 12 inches thick. The operator filled the hole with brick, gravel, clay, etc., to the limestone shell, and then with the tools drove lead into the limestone shell, just as a dentist would fill a hollow tooth. Finally the lead was packed tightly enough to hold the water back temporarily. Cement was then dumped on top of the plug and the bottom water shut off effectively.

However, lead plugs, lead wool, or packers should not be used alone unless the hydrostatic head of the water is very small. For a discussion of the use of lead plugs and lead wool, the reader is referred to Bulletin 163⁸⁵ of the Bureau of Mines.

The possibilities of using the spiral plug in shutting off bottom water have been discussed by Goodrich,⁸⁶ who points out that cement pumped or dumped into a well may be honeycombed by the action of gas or flowing water. A spiral plug affords a friction hold that keeps the plug in place.

INTERMEDIATE WATER.

If intermediate water is present, the operator must exercise great care in protecting the upper oil sands while producing from the lower sands. In wells producing from the lower sands only, the upper oil sands should be protected by placing behind the water string either mud-laden fluid or a liberal quantity of cement—enough to make sure that the top of the cement is actually above that of the upper oil zone. This will effectually protect the upper sands from middle water. The ideal method is to produce from the upper sands until they are exhausted (see pp. 82 and 83 and fig. 19), then deepen

⁸⁴ Lewis, J. O., and McMurray, W. F., Use of mud-laden fluid in oil and gas wells: Bull. 134, Bureau of Mines, 1916, 86 pp.

⁸⁵ Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163, Bureau of Mines, 1918, pp. 85-86.

⁸⁶ Goodrich, H. B., The use of the spiral plug in shutting off water in Mid-Continent wells: Nat. Pet. News, May 21, 1919, p. 35.

the wells, cement below the intermediate water, and produce from the lower sands, but this would seldom be practicable. Often the operator will want to produce from the lower zone, because of its being more prolific, its oil being higher in gasoline fractions or furnishing better lubricating stock, or his neighbors may be producing from that zone. In any event, every effort should be made to protect the upper sands from water if it is desirable to produce from the lower zone.

If a well, producing from both the upper and lower oil zones, is making a larger quantity of water from an intermediate sand, either the hole should be plugged from the bottom to a point above this sand and production taken from the upper oil zone, or else a string of casing should be cemented below the intermediate water sand. In plugging, it is best to use a large amount of cement to protect the lower sand. Where a new string is cemented below the intermediate water, enough cement should be placed behind the pipe to assure proper protection of the upper oil zone.

In some fields, intermediate water can be pumped out as fast as it comes into the hole, but the operator should know definitely that he is pumping out all the water that reaches the well. A certain size of pump will lift only so much fluid, and if all is not lifted much may be working back into the oil sands. Furthermore, the water level in the hole may be low and as a result the pump may be skimming the oil off the water. (See discussion of fluid levels, pp. 193 to 197.)

Goodrich⁸⁷ suggests the use of a liner having two packers, one at the top and another at the bottom, for shutting off an intermediate water. The liner would be set opposite the water sand and the packers are supposed to confine the water to the sand. Where the water has any appreciable head, it is doubtful whether the method would give satisfactory results in most wells.

EDGE WATER.

The problem of properly handling edge water is difficult but is one of the most important in production engineering. Water in a local lenticular sand should not be mistaken for edge water. Encroaching edge water ordinarily entraps large quantities of oil, which is lost to the operator; hence, it is extremely important that he restrain the encroaching water as long as possible, in order to get the maximum recovery of oil. The following methods are suggested for restraining encroaching edge water:

1. Force compressed air into those wells nearest the edge water line, thus holding back the water, while permitting increased pro-

⁸⁷ Goodrich, H. B., Water encroachment and some methods for protecting the field: Nat. Pet. News, Apr. 2, 1919, pp. 65-68.

duction in the wells upslope. This method, as far as the writer knows, has not been demonstrated in practice.

2. Keep the edge wells pumping in order to remove the water from the sand as rapidly as it encroaches. A barrier could thus be created to protect the rest of the field. The desirability of this would depend upon various considerations, many of them financial. In a large field the wells on the edge of the field often protect the interior wells.

3. Drill ahead of the approaching water, and plug the well as soon as the water becomes troublesome. The reasons for this suggestion are as follows:

For the purpose of obtaining a maximum production, a careful study should be made of drilling costs and production records in order to determine the greatest number of wells that can be drilled with profit. In short, the encroaching edge water is certain to entrap much of the oil, so the operator should figure to get the greatest profit per barrel of production. He should follow the edge-water encroachment carefully, because the advance may be for a limited distance only.

In fields where there are a number of oil sands edge water may be present in the upper, middle, or lower sand. If edge water occurs in the upper sand and has advanced to the well, it should be regarded as top water and a shut-off made below this sand, as discussed on page 143.

Edge water in an intermediate oil sand may be handled by plugging the hole with cement from the bottom to a point above the water and producing from the top sand in that well. In doing this great care should be taken that no water is allowed permanent access to the lower oil zones. Another way is to land a water string below the edge-water sand and make the well produce from the lower zone. It is important in such a case that the top oil sand be protected properly. (See discussion on pp. 140 to 143.)

If edge water appears in the bottom oil sand of a well, the bottom of the hole should be plugged with cement and production taken from the sands above. (See fig. 23 and discussion, pp. 99 and 100.)

The corrective measure suggested are intended for wells where the edge water is present in large volume under strong hydrostatic pressure. If the volume of water is small, it may be cheaper to produce the water with the oil.

WATER IN THE BASE OF AN OIL SAND.

As previously stated, an operator, before deciding that water occurs in the base of an oil sand, should make sure that the water and oil are not separated by a small break. He should bear in mind the distinction between a small impervious streak a foot thick or

less which is local in extent and a parting of uniform occurrence throughout the field, for in the latter event the water would be termed "bottom water." A local parting of less than 1 foot may separate the oil and water, and unless this parting has some particular feature noticeable in drilling, it will probably be passed by unnoticed. On the other hand, a sand may be a barrier between the oil and water in one well because of local cementation with calcite, silica, etc., whereas in another well where the cementation is not so tight the water will occur in the base of the sand.

The placing of a thin cement plug of an exact thickness by ordinary dump bailer methods is difficult, but nevertheless the well should be plugged in stages with cement and tested. In each test the operator should see if the cement is hard, and plug only a few feet at a time.

The McDonald method of shutting off water in a well where water occurs in the base of the oil sand has been successfully applied in the Illinois field. This method has been described by Kay⁸⁸ and by Tough.⁸⁹

When the water and oil occur together in a uniformly porous sand and the water is under a high head, the application of the McDonald method, or any other, can at best only delay water encroachment, for eventually the water will become master. However, in a practical sense no sand is uniformly porous. Figure 26 is a hypothetical sketch to show how water in the base of an oil sand may trap a large body of oil if the sand is evenly porous.

In the figure, *A* represents the original contact of oil and water; *B* shows the contact after much oil has been withdrawn. The water follows the withdrawn oil, and the contact between the oil and water assumes an irregularly conical shape. The shape of this contact will depend partly on the uniformity of the sand porosity and the rate of withdrawal. The oil will, of course, work out more slowly from the tighter parts of the sand, and in these places a great deal of oil will be trapped below the oil-water line, as the water will reach to the well through the more open parts of the sand. With a sand of fairly uniform porosity the water will advance the most rapidly from below and traps large bodies of oil underground, more or less as represented by *C*, figure 26.

The hope of the operator for recovering as much oil as possible lies in the fact that all sands are not uniformly porous and that they contain local impervious partings of shale, clay, or tightly cemented layers.

⁸⁸ Kay, F. H., Petroleum in Illinois in 1914-15: Illinois State Geol. Survey, Bull. 33, 1916, pp. 87-88.

⁸⁹ Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163, Bureau of Mines, 1918, pp. 82-85.

Obviously, impervious or semiimpervious streaks will retard or even prevent water encroaching. In C, of figure 26, an impervious streak in the bottom of the well would permit the use of cement to shut off water coming into the well; then oil could be drawn from the upper part of the sand in that well.

These impervious streaks are rather common in many oil-producing strata and the operator should look for them when drilling a

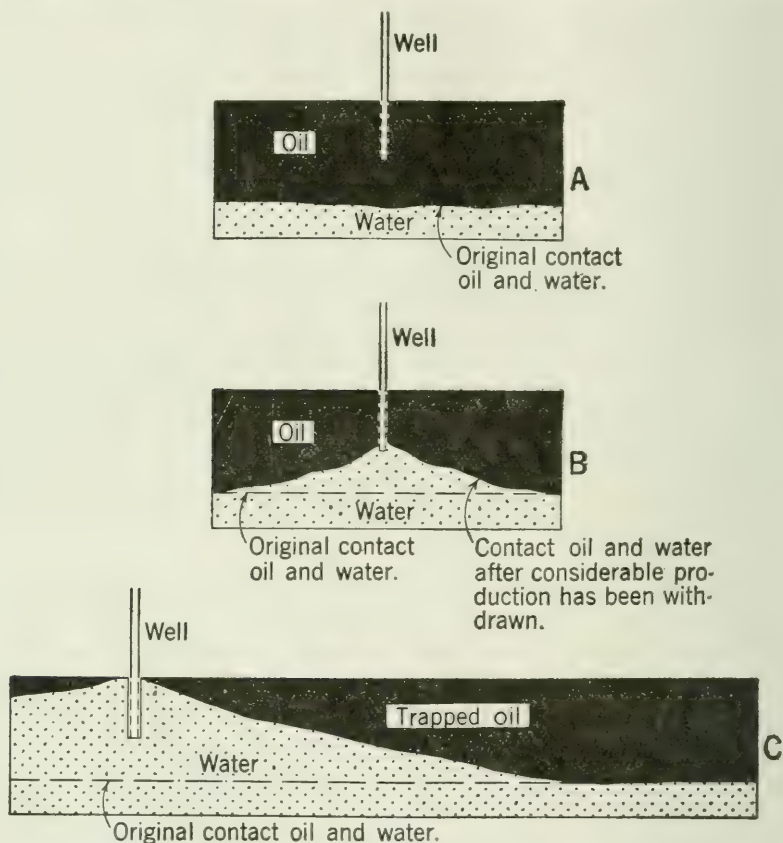


FIGURE 26.—Sketch showing how water in base of oil sand may trap oil. Impervious partings in the sand often permits a temporary or even permanent water shut-off in a particular well.

well. In a producing oil well which is making water, plugging should be tried even if the water and oil occur together, in the hope of finding a parting in the sand.

WATER IN A LENTICULAR SAND.

All sands are more or less lenticular. A small local lens of water may occur any place in the productive zone and should be handled as a top, bottom, or middle water, according to its location.

PROTECTION OF UPPER OIL AND GAS SANDS.

When the largest production lies in the lower oil sands, many operators drill to those sands without regard to the less productive sands above. In a field subdivided into small leases or ownerships there is often much line-well drilling, the wells being sunk with all possible speed to the big producing sand. Each operator tries to beat his neighbor to this sand so as to obtain the benefit of the flush production.

Many of the upper sands are good for 500 or more barrels of oil a day, and it is highly important that they be properly protected against waste and water until such time as the operator desires to produce from them. Such protection can be had at a reasonable cost, and it is only good business to have these sands in reserve.

In wells drilling with rotary tools only one string of casing may be used between the top of the producing oil sand and the surface. Obviously, unless mud has sealed off the water sands and the upper oil and gas sands, the water can work up into these sands; also the oil or gas can escape into other porous formations or to the surface between the wall of the hole and the outside of the casing.

These sands may be protected when a rotary is used by circulating thick mud fluid for several days before landing the water string. This mud should be left behind the water string after it is landed.

In a well drilled by cable tools the oil and gas sands can be protected by the use of either mud-laden fluid or cement.⁹⁰ It may be advisable to cement a string of casing below each upper oil or gas sand.

In this connection attention is called to figures 28 to 36 (pp. 161 to 169) presented in the chapter dealing with losses caused by unsystematic casing.

Upper sands are difficult to test once they are cased off, and if practicable a drilling well should be stopped at the proper depth to make necessary tests.

ENCROACHMENT OF INTERMEDIATE WATERS AND METHODS OF PROTECTING UPPER OIL SANDS BY THE USE OF MUD-LADEN FLUID—EAST SIDE FIELD, COALINGA, CALIF.

By E. D. NOLAN.

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GENERAL STATEMENT.

This chapter deals with methods used in solving problems in the East Side field, Coalinga, Calif., caused by the encroachment of edge

⁹⁰ Lewis, J. O., and McMurray, W. F., The use of mud-laden fluid in oil and gas wells: Bull. 134, Bureau of Mines, 1916, 86 pp.; Tough, F. B., Methods of shutting off water in oil and gas wells: Bull. 163, Bureau of Mines, 1918, pp. 24-85.

water in an intermediate zone of the producing oil horizons. Detection of the encroachment of this water was possible by the use of reliable and fairly complete records, as well as the knowledge of a competent foreman, who had watched the development of this field over a number of years.

The author wishes to acknowledge his indebtedness to Mr. B. H. van der Linden, production manager of the Shell Co. of California, for the data which made this article possible, to Mr. W. C. McDuffie for many helpful suggestions, and to Mr. J. A. Trudeau, who prepared the accompanying illustrations.

The producing oil measures in the East Side field comprise the whole of the Vaqueros formation, exclusive of the Big Blue shale, which is referred to that horizon by Anderson and Pack.⁹¹ This formation is a series of loose sands and shales about 600 feet thick. About midway in the formation is a persistent black shale. Its position with reference to the formation is shown in figure 27, where the shale is marked "B."

In general the structure of the East Side field is that of a plunging anticline. The axis of this anticline lies as shown in Plate XIX; the detail structure is brought out by the contour lines showing the position of the top of the Big Blue shale with reference to sea level.

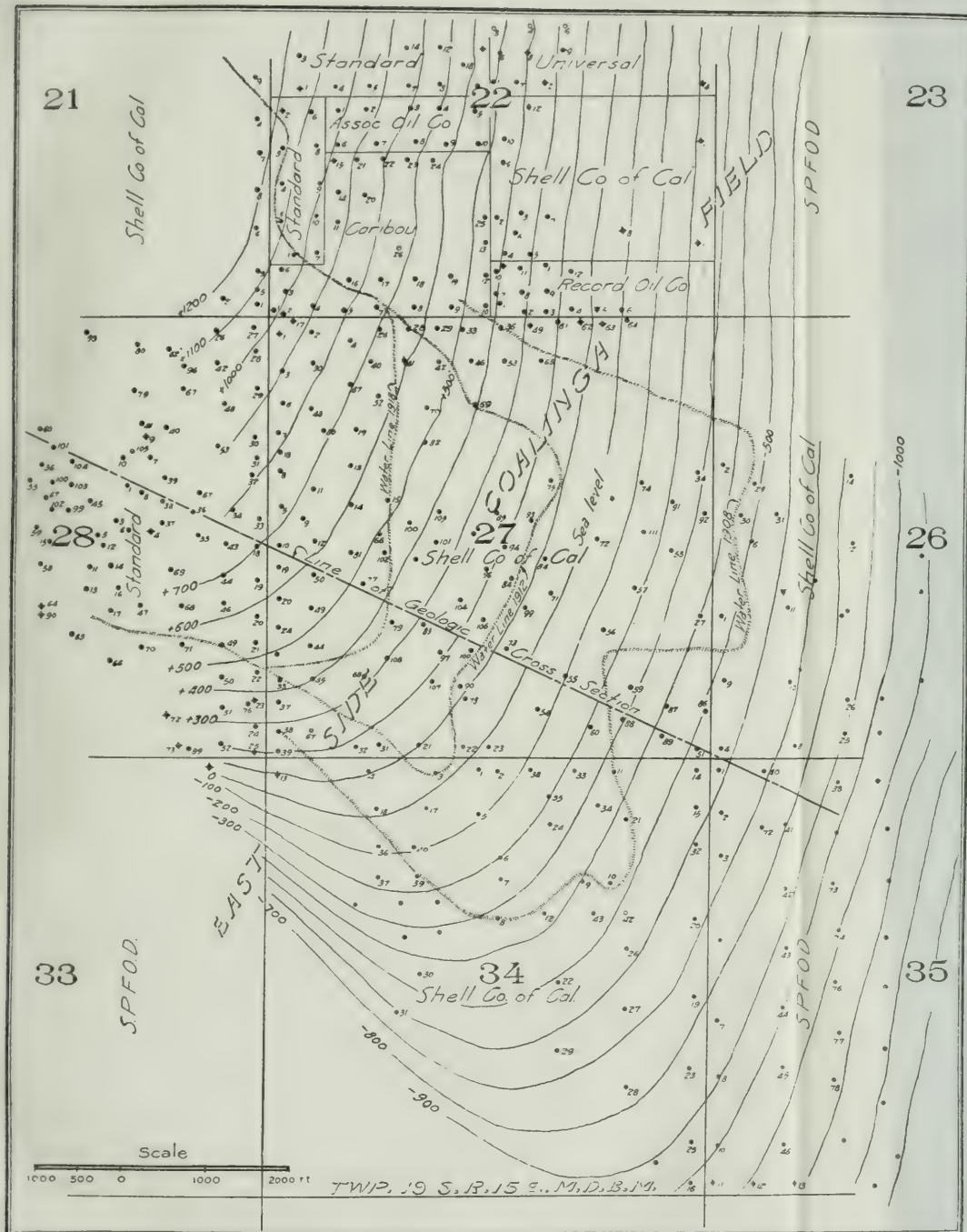
EARLY DEVELOPMENT.

Development of the East Side field began about 1901. The first wells were drilled in the general vicinity of the NW. $\frac{1}{4}$ of sec. 27, T. 19 S., R. 15 E., where producing oil sands were found at the shallowest depth. In these pioneer wells the whole of the Vaqueros formation, except the Big Blue shale, proved to be oil bearing; no water sands were encountered below that shale.

As development proceeded down the dip of the anticline toward the southeast, water began to be encountered. At that time practical oil men were unable to account for this water, but it is now known to have been intermediate water lying on top of the black shale marked "B" in figure 27.

Shortly downslope from the point at which water was first encountered extensive oil showing ceased to be found in that part of the Vaqueros formation lying above the black shale. Thus the formation is separated into an upper horizon and a lower one, the dividing line being the black shale and the edge water lying on top of it. The productive limit of the upper horizon corresponds closely to the point at which water was first encountered.

⁹¹ Anderson, Robert, and Pack, R. W., *Geology and oil resources of the west border of the San Joaquin valley north of Coalinga, Calif.*: Bull. 603, U. S. Geol. Survey, 1915, p. 84.



SKETCH SHOWING ENCROACHMENT OF EDGE WATER COALINGA ANTICLINE, FRESNO CO., CALIF.



A. CRATER OF GAS WELL TAKEN AFTER A LOSS OF MILLIONS OF CUBIC FEET OF NATURAL GAS.

This well afforded gas for blowout in Plate XX, B.

(Photo by E. W. Wagy.)



B. CRATER FORMED BY GAS ESCAPING TO THE SURFACE 300 FEET FROM THE WELL. The gas migrated from the well up through formation and escaped in blowouts as far as 800 feet from the well.

(Photo by E. W. Wagy.)

As oil was drawn from the upper productive sands, this edge water encroached rapidly in the sand immediately on top of the black shale and probably more slowly in the sands lying between this one and the Big Blue shale.

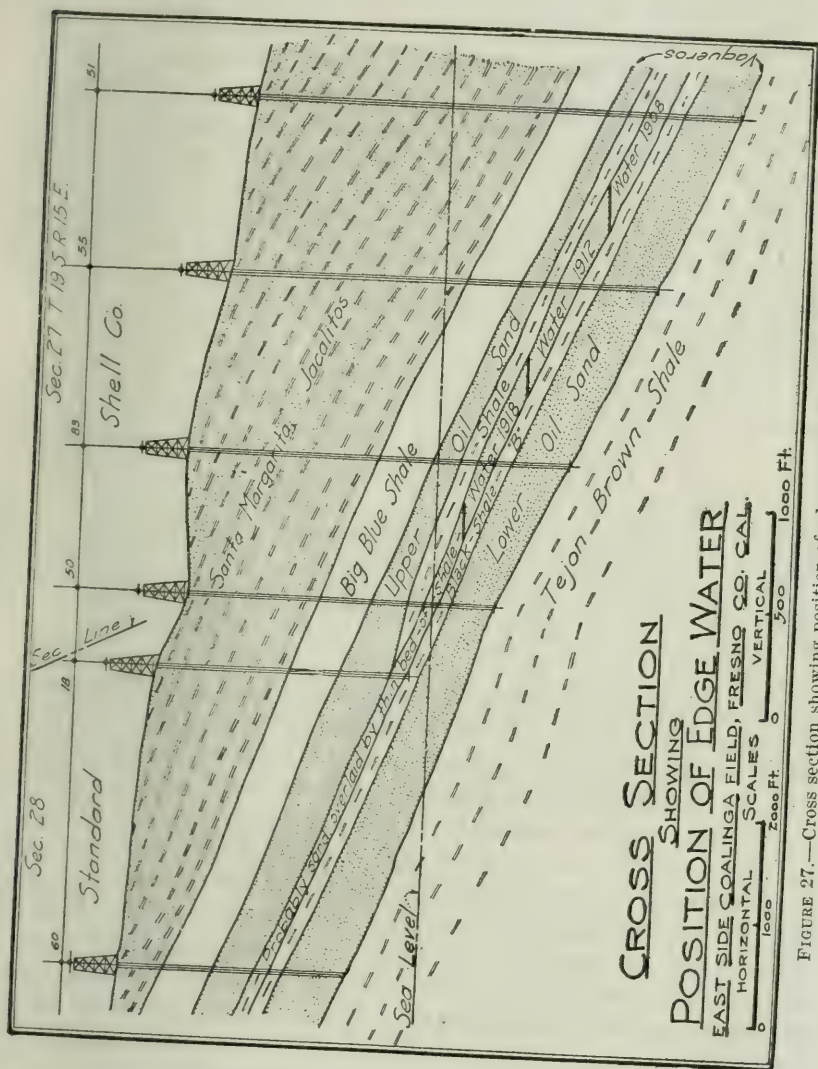


FIGURE 27.—Cross section showing position of edge water, East Side field, Coalinga, Calif.

ORIGINAL WATER LINE.

The original known limits of this water are shown approximately in Plate XIX as the water line for the year 1908. Its location on the map involved the study of well histories and early production records, of which many are far from complete. Fortunately, the present production foreman of the Shell Co. of California, Mr. J. A. Mc-

Laughlin, was foreman at that time. He suspected that the water was encroaching long before positive proof was to be had. He has been able to supply much valuable information, particularly in interpreting the production records of that time.

The water line of 1908 was taken as the original line because presence of the edge water was first established in that year. This line was, in general, determined by liberal interpretation of the following facts: The first well that proved this water in the original drilling seems to have been well 8 on section 34. Mr. McLaughlin states that the well always showed water, but the popular opinion was that top water was being let in by neighboring wells. In order to shut off this supposed top water, the well was redrilled during the period August, 1908, to September, 1910. Then the well, still open to the whole series of Vaqueros sands, was put back to producing. Its record was as follows:

Production record of well 8, from October, 1910, to October, 1911.

	Oil, barrels	Water, per cent		Oil, barrels	Water, per cent
1910			1911—Continued.		
October.....	3,755	2.4	April.....	27,516	37
November.....	39,490	10	May.....	26,113	37
December.....	43,904	14	June.....	21,586	42
1911			July.....	18,920	47
January.....	37,338	16	August.....	4,755	70
February.....	30,968	18	September.....	1,288	91
March.....	30,680	34	October.....	2,038	85

Continued efforts were made during 1912, 1913, and 1914 to shut off this water, but on account of the belief that it was top water well 8 was not properly repaired until 1914. Wells 9, 12, and possibly 11 on section 34 seemed to have encountered water in the intermediate sands in 1907 and 1908. The record of well 10 on section 34 would prove that water broke in during 1909. Well 38, in the southwest quarter of section 27, was completed in 1908 and seems to have been just on the edge of encroaching intermediate water. Well 51, in the southeast corner of section 27, when first completed in 1909, produced about 40 per cent water, showing definitely that the intermediate water had passed this well at that time. Well 49, on the north line of section 27, was completed in 1909 and made about 5 per cent water with its initial production. The records for wells 35 and 36 are rather incomplete, but, according to Mr. McLaughlin, they made very little water until 1909.

Thus, prior to the year 1908 there was no evidence to prove that edge water existed. The water line for that year drawn on the maps is necessarily an approximation, but very likely the water had not then appeared in any wells upslope beyond the line drawn. Of

course, certain of the wells discussed came in as flowing wells with productions of 800 to 1,000 barrels a day. Among these flowing wells were Nos. 6, 8, 10, and 11 on section 34, Nos. 27 and 34 on section 27, also Nos. 1 and 2 on section 26. Possibly edge water had been present in these wells from the first, but on account of the high gas pressure was not able to make itself felt until the pressure had sufficiently declined. The other wells mentioned were pumping wells yielding only 100 to 200 barrels of oil a day, and likely such a condition did not exist in them.

The relation of this intermediate water to the black shale and also to the upper and lower oil zones is shown on the ideal section in figure 27 (p. 151).

ENCROACHMENT OF WATER FROM 1908 TO 1912.

From the year 1908 this intermediate water gradually encroached on the productive territory toward the northwest. A number of wells came in as producers of clean oil and afterwards slowly went to water. The wells along the original water line often made as high as 600 to 800 barrels of water a day, but the wells higher up slope into which the water encroached seldom made more than 100 barrels.

The production records indicate that on section 27 water broke into wells 22, 31, 33, 35, 36, 46, 55, and 69 between 1908 and 1912. At the same time wells 71 and 73 found water in the original drilling. Well 22 during the year 1910 averaged about 14 per cent water, but during 1911 the water content increased from about 12 or 13 per cent at the beginning of the year to 21 to 38 per cent at the end of the year. Water first appears in well 31 in April, 1912; the production for 1912 was as follows:

Production of well 31 in 1912.

1912	Oil, barrels.	Water, per cent.	1912	Oil, barrels.	Water, per cent.
January.....	8,240	.....	July.....	2,173	25
February.....	7,201	.....	August.....	7,052	32
March.....	7,172	.....	September.....	2,868	22
April.....	6,103	9	October.....	2,843	22
May.....	3,045	10	November.....	2,975	26
June.....	2,458	18	December.....	2,498	26

Well 54 produced in January, 1910, 10,477 barrels of oil, with 2.2 per cent water; September, 9,032 barrels of oil, with 4 per cent water; December, 3,512 barrels of oil, with 8.5 per cent water; January, 1911, 2,463 barrels, with 15 per cent water; May, 2,927 barrels, with 20 per cent water; December, 3,698 barrels, with 18 per cent water.

On section 34, production records indicate that water broke into wells 2, 3, 4, 5, and 6 between the years 1908 and 1912. For example, in well 5 the production for January, 1910, was 4,062 barrels of oil, with 15 per cent water; for January, 1911, 4,222 barrels, with 17 per cent water; and for January, 1912, 5,162 barrels, with 21 per cent water. In well 3 the production for January, 1910, was 6,963 barrels, with 0.3 per cent water, and for December, 1910, 4,438 barrels, with 11 per cent water.

The water line for 1912 on the map is based principally on the histories of the wells mentioned, which are much more complete than those of the older wells. The water line as depicted for the year 1912 is probably much more accurate than the original water line for 1908. Well 1 on section 34 is included within this limit, although in this well water in large quantities did not appear until the year 1919. The well produced in January, 1917, 2,698 barrels of oil, 90 barrels of water; in January, 1918, 1,949 barrels of oil, 467 barrels of water; in January, 1919, 2,132 barrels of oil, 800 barrels of water; and in March, 1919, 2,323 barrels of oil, 2,126 barrels of water.

1918 WATER LINE.

The intermediate water has continued to encroach; the water line for the year 1918, shown in Plate XIX, is drawn between the wells that are practically free of water and those known to yield the intermediate water. Water analyses have enabled the company to recognize easily the presence of this water, which differs decidedly in character from either the top or the bottom water. Therefore, in later years mechanical tests that indicated intermediate water have been checked by water analyses.

RATE OF ENCROACHMENT.

Many interesting facts have been learned by studying the encroachment of this intermediate water. The rate of encroachment seems to have been gradually decreasing. For example, along the line of the cross-section in Plate XIX, the water encroached a distance of 1,600 feet during the period 1908 to 1912, or at the rate of 400 feet per year. Along the same line the water encroached only 1,200 feet for the six years between 1912 and 1918, or 200 feet per year. The cause of the slower encroachment is due to the lower hydraulic head as the water moves up the dip.

The volume of water in the wells upslope is much less than in the wells where it was first encountered. Many of these early wells produced more than 500 barrels of water a day. Now certain producing wells, such as Nos. 70, 82, and 83 on section 27, which are open to this intermediate sand, only make 40 to 90 barrels a day.

A further proof that the water is encroaching is the increased volume of water in any given locality as time elapses. For example, wells 54 and 55 on section 27 produced 100 barrels of water daily, before being repaired in the year 1914. Well 111 in the same locality was, on account of a faulty water string, producing intermediate water in the early part of 1919; the volume of water pumped was 250 to 400 barrels daily. Proof that this was all intermediate water was obtained from water analyses. Well 78, near the south line of section 27, encountered this water immediately under the shoe of the water string in 1916. The volume of water was tested by bailing and amounted to about 50 barrels a day. Well 83 upslope from this well was completed in 1917; after the well had been producing for a few months, the intermediate water entered and increased to approximately 100 barrels daily.

In well 90 the hydraulic head of the intermediate water was established as 453 feet above the top of the sand. The structural contours in Plate XIX, which depict the general structure, indicate that with this hydraulic head the water line is very near the limits of possible encroachment. Along the front of the encroaching water the hydraulic head is now so low and the volume near the present water line is so comparatively small, as illustrated by the productions of wells 70 and 82, that the water will not likely encroach into more than three or four new wells nor in sufficient quantity to require repair work.

RELATION BETWEEN STRUCTURE AND ENCROACHMENT.

The original position of the intermediate water and likewise its encroachment have been largely determined by the underground structure. Originally the water line came up on the flanks of the anticline, as shown in Plate XIX, in the S. $\frac{1}{2}$ of section 28 and the SW. $\frac{1}{4}$ of section 22. Along the crest of the anticline, however, the accumulation of oil and gas had forced the water far down slope. As the oil and gas were drawn off by the rapidly increasing number of wells up slope, the water began to encroach, as shown by the successive water lines in Plate XIX. The greatest advance took place along the crest of the anticline, practically no advancement occurring on the flanks. A study of the structural contours indicates the cause. With a hydraulic head of only 453 feet at well 90 in section 27, it is quite evident that in section 22 there would be practically no head on the water at its present limit. This limit in that section is also practically the original position when development of the field first began.

MUD-LADEN FLUID METHOD OF DRILLING DEVELOPED TO HANDLE THE CONDITIONS BROUGHT ABOUT BY ENCROACHING WATER.**NECESSITY OF PROPERLY PROTECTING UPPER OIL SANDS.**

The encroachment of edge water, as described in the preceding pages, has necessitated redrilling and repairing of many wells. In these wells both water and oil sands had to be left behind a single string of casing, for the upper oil horizon was commercially productive over the whole of section 27 and is still productive in the north part of section 34, as well 1 on that section obtains its production from the upper horizon.

In order to insure proper protection of this upper oil horizon, it seemed desirable to employ some method other than merely cementing a string of casing, else there might be intercommunication between the overlying sands, and the intermediate water, although shut off from the main lower zone, might flood the upper horizon. For this purpose the possibilities of mud-laden fluid, as used in the Oklahoma fields, were seriously considered. The proper method of drilling a well at this time would seem to be the cementing of a string of casing in the Big Blue shale, as shown in figure 27, for the purpose of shutting off the top waters found in the overlying Santa Margarita and Jacalitos sands. Then a second string of casing should be cemented in the black shale—shown as "B" in figure 27—after thorough mudding. This mudding before cementing should thoroughly seal the sands in the upper oil horizon and effectually protect them from all possible damage. A third string of casing would then be used to penetrate into the lower oil horizon. In this connection explanation should be made that the upper oil sands though commercially productive are not nearly as rich as the lower main horizon; and present prices of oil and the high cost of drilling in California fields make it essential that wells be finished in the lower horizon.

USE OF MUD-LADEN FLUID IN ROTARY WELL TO MUD OFF UPPER OIL SANDS.

Further consideration of the subject brought the suggestion that the well be drilled by rotary to the black shale, the hole mudded under merely hydraulic head of fluid in the hole, and the string of casing cemented in the black shale. By this method the top water sands, the upper oil zone, and the intermediate water sand would all be exposed behind the single string of casing. Mud pumped in under normal rotary conditions and sufficient cement to extend above the top of the uppermost oil sand would be depended upon to prevent any intercommunication between the several layers and to protect the upper oil horizon from damage by infiltrating water either from above or below.

The operators were well aware that in Oklahoma the mud-laden system had been very successful, but had always been employed

where a pressure of many hundred pounds could be placed on the well for the purpose of forcing the mud back into the sands. With the rotary method outlined above no additional pressure could be applied to the mud column. However, use of the method would permit the operators to complete wells with only two strings of casing, thus saving one string of casing, and would also shorten the time of drilling by many days.

A thorough test of this method was made by drilling well 90 on section 27, by rotary, only 150 feet upslope from well 78, which was producing from the upper horizon. In case the upper oil sands were not properly protected in well 90, infiltrating water should quickly make its appearance in well 78. The general scheme of drilling this test well was planned at a conference between the Shell Co. of California and the California State Mining Bureau. It was thought that such a test well would go a long way toward proving the efficiency of the proposed method, at least for the Eastside field at Coalinga, before operators had made any wide use of it with possible great damage to the producing territory.

The well (No. 90) was spudded on September 10, 1917, and drilled to a depth of 1,361 feet by rotary, at which point a string of 10-inch casing was cemented in the black shale. The upper oil and water sands were mudded while passing through. No additional head was used; the hydraulic head of the fluid was sufficient to mud the hole as fast as it was drilled.

Red mud was circulated for five days after the drilling ceased and before the pipe was cemented. The hole took practically no mud during this period, proving that the formations were thoroughly mudded while passing through them. The 10-inch casing was then cemented at 1,631 feet with 200 sacks of cement. The hole is a 15½-inch hole with 5 feet of 14-inch hole at the bottom where the 10-inch casing is landed. Therefore, the cement is estimated to extend up behind the casing about 300 feet, or above the top of the upper oil sand, and is a further guaranty that the sands are protected.

Production of well 78, section 27, during this period.

Month.	Oil.	Water.	Water in suspension.	Gravity.
1917.	<i>Barrels.</i>	<i>Barrels.</i>	<i>Per cent.</i>	<i>° B.</i>
July.....	1,138	88	1.7	26.2
Aug.....	1,111	77	.6	26.3
Sept. ^a	1,017	101	.2	26.3
Oct.....	1,043	95	.5	26.4
Nov.....	1,035	77	(b)	26.2
Dec.....	1,046	83	(b)	27.0
1918.				
Jan.....	974	70	(b)	27.0
Feb.....	988	51	(b)	27.1

^a Drilling of well 90 started on Sept. 10. The well was completed in the same month.

^b No centrifuge tests available.

The pumper reported that muddy water appeared in well 78 during the time well 90 was drilling through the upper oil sands.

Well 90 was finished in September, 1917; at the date of writing, November, 1919, well 78 was making even less water than before the drilling of well 90.

In addition many other wells have been drilled by the same method used in well 90. So far no ill effects have been observed from the use of this method.

GENERAL SUGGESTIONS IN USE OF MUD-LADEN FLUID METHOD.

The following general rules have been developed by the Shell Co. for drilling wells by the rotary method with the use of mud-laden fluid:

1. No additional head is necessary to properly mud the sands, the hydraulic head of the fluid is sufficient.

2. Fast drilling and rapid rotation give the best results. Rapid rotation is conducive to effective mudding because of the contact of the drill pipe with the sides of the hole and constant tendency to force the mud into the formation. Rapid rotation also causes the solid particles to seek the sides of the hole on account of centrifugal force.

3. The mud is thickened when the top of the upper oil horizon is encountered. The specific gravity of the mud, while penetrating the upper oil horizon and intermediate water sand, is maintained as heavy as successful drilling will permit. The specific gravity of the mud at this period ranges from 1.11 to 1.15.

4. Mud is circulated in the hole for 1 to 3 days before the casing is cemented. At this period some holes take no mud at all, others take a little, but none of them will take any mud after 24 hours.

5. The company had no difficulty in getting cement to set in rotary holes. Large quantities of cement—that is, 200 to 250 sacks—are forced into the well by the Perkins method, which has been found very successful in rotary holes. Laboratory tests made by the company indicate that strength of cement is affected very little, even when mixed with as much as 30 per cent of mud.

SAVINGS OF TIME AND MONEY BY THIS METHOD.

The successful application of the mud-laden fluid method in rotary drilling, to meet the conditions in the Eastside field at Coalinga, resulted in a great saving of both in the drilling cost of the wells and the time necessary to complete the drilling. One entire string of casing is eliminated by this method, which results in a saving of not less than \$6,000 per well. In addition, wells are completed in about two months' less drilling time than would be possible for any other

method which would give adequate protection to the territory. The companies, therefore, get the benefit of two months' additional production. For additional details of this method the reader is referred to Bulletin 84, of the California State Mining Bureau.⁹²

CASING DEPTHS.

An outline of various problems to be covered by oil-field engineers is given on pages 5 and 6. Naturally these problems overlap—for example, the proper depth to land the water string is dependent largely upon the occurrence of water sands, previously discussed under "Water problems." On account of this overlapping, the reader should be familiar with the preceding information so that it can be readily referred to.

After the cross sections are compiled, the engineer is in a position to advise the superintendent as to what depth he should land the casing for a water shut-off. Improper casing depths may cause shutting off of productive oil sands (see fig. 37 and discussion on pp. 169 to 173) or may allow water to work into productive oil zones (see figs. 28 to 36 and discussion, under "Underground losses," pp. 160 to 166).

In a limited area, drilled in an ideal manner, the water shut-offs are a constant distance from the marker. The proper shut-off point lies below the upper water sands, but above the producing oil zone. Often this point is difficult to determine, when a water sand is found above the oil zone, and there may be a tendency to land the pipe too low. In such localities a well that makes no water and whose water string has the highest landing stratigraphically, may serve as a guide.

The ideal shut-off point is several feet above the producing zone, in a tough shale or hard break which assures a firm seat for the casing shoe. Before landing the casing for a shut-off, several feet of small hole may be drilled to insure a close fit for the casing shoe. The farther the casing extends below the water sands the better the chances are for cavings to fall in around the pipe; this often helps to hold the water back (see fig. 18, p. 81) from the well and prevent future leaks. The operator, however, should be careful that he does not land the water string too low and thereby shut off productive oil and gas sands behind the pipe.

With the cross sections correlated, proper casing depths can usually be selected correctly within a few feet. For example, suppose a well was to be drilled midway between well 6 and well 8, of the Sauer Dough property. (See Pl. III, p. 40.) A vertical line representing this well would be drawn on the cross-section map midway between wells 6 and 8. The proper shut-off point for wells on this property

⁹² Collom, R. E., Comparison of various methods of excluding water from oil wells in California; Bull. 84, Calif. State Min. Bureau, 1919, p. 77.

happens to be in the shale below the "sulphur-water" zone and a few feet—approximately 5 or 10 feet, at this location—above the top of the Sauer Dough oil sand. Next the elevation of the derrick floor—or if no derrick is standing, the estimated elevation of the derrick floor when established, using the surface elevation at the well location as a basis—is determined as being, say, 1,280 feet above sea level. Then this distance is scaled off, measuring from the sea-level line, on the vertical line drawn between wells 6 and 8. The proper depths to land the water string would be at a point about 5 or 10 feet above the intersection of the vertical line with the line representing the top of the Sauer Dough oil sand. The depth below surface to land the water string would be obtained by scaling on the vertical line between this point and the point representing the elevation of the derrick floor.

In scaling distances proper allowance should be made for any shrinkage of the paper and the same unit of measure used as in the other wells. Any other cross sections that pass through the proposed well should be used as a check.

Water shut-off points can be selected by use of structural contour maps. For example, assume that the structure contours are below sea level, that the well location is on the 500-foot contour, that the derrick floor has an elevation of 1,200 feet above sea level, and that the proper shut-off point is 600 feet below the marker on which the contours are based. Then the proper casing depth would be 1,200 plus 500 plus 600, or 2,300 feet below the derrick floor. If the contours were above sea level, the 500 feet would be subtracted instead of added, or the proper casing depth would be 1,300 feet below surface.

UNDERGROUND LOSSES.

GENERAL REMARKS.

Underground losses of oil and gas probably far exceed all the waste at the surface, but these are not visible. There are no parallel cases, one where the field was saved by corrective measures and the other where it went to ruin by lack of corrective measures. There is plenty of evidence, however, that underground wastes have lost forever thousands of barrels of oil. The engineer should do all he can to bring these losses to the attention of the operator and to suggest means for their prevention and correction.

The principal losses are probably from oil unnecessarily remaining in the sand, by oil being trapped by water, or by dissipation of gas pressure. The losses of oil from poor extraction is covered on pages 161 and 200. The loss of oil by invading water has been discussed previously under "Water problems," and is covered further in the following discussion on losses caused by improper or unsystematic

casing. The dissipation of gas is an important problem, too large to be covered in this paper. Many operators are inclined to let the well flow wide open in order to get rid of the gas. Gas is a prime factor in moving the oil to a well, and perhaps much greater recovery could be accomplished by making the well flow against back pressure.

LOSSES DUE TO IMPROPER OR UNSYSTEMATIC CASING.

There has been much discussion⁹³ relative to the underground wastes of oil and gas by improper and unsystematic casing practices. Such wastes are caused by water trapping the oil and by the oil and gas migrating into other porous formations. These kinds of losses are often due to improper casing depths. In general, the proper place to land the water string is just below the top water and above the upper oil sand, but in his anxiety to go deep enough to shut off all water the operator may land it below an oil sand. This is particularly true in a new field where flush production is a factor, or where there is competitive line well drilling. When oil sands are cased off, water may work down into them unless cement or mud-laden fluid is used.

When neither cement nor mud-laden fluid is used, often gas or oil in a sand above the water shut-off escapes between the casing and the wall of the hole. Such a waste should be avoided.

Water gains access to producing formations by improper casing methods, as well as poor water shut-offs, and by drilling into bottom water. The losses due to water have been previously covered in considerable detail (pp. 68 to 159).

As various standard publications on underground wastes by improper casing methods are available, this subject need not be treated in great detail here. The engineer should make every effort, however, to provide against such waste and insist upon the property being operated from a standpoint of conservation. Figures 28 to 36, which are self-explanatory, show the more common means or causes of these wastes.

Other improper casing methods are shown by Beal.⁹⁴

LOSSES IN RECOVERY METHODS.

The question of increasing the recovery from oil and gas sands is a large and important production problem. This is covered briefly as a special problem for the petroleum engineer on page 200.

⁹³ Lewis, J. O., and McMurray, W. F., The use of mud-laden fluid in oil and gas wells: Bull. 134, Bureau of Mines, 1916, 86 pp.; McMurray, W. F., and Lewis, J. O., Underground wastes in oil and gas fields and methods of prevention: Tech. Paper 130, Bureau of Mines, 1916, 28 pp.; Second Annual Report of the State Oil and Gas Supervisor of California, 1916-17. Calif. State Min. Bureau Bull. 82. 1918. pp. 12-17.

⁹⁴ Beal, C. H., Geologic structure in the Cushing oil and gas fields, Oklahoma: U. S. Geol. Survey Bull. 658, 1917, Pl. XI.

LOSSES DUE TO A WELL OUT OF CONTROL.

Underground losses may be indicated to some extent by certain surface evidences. In some fields the wells have been shut in, as there was no surface storage available or no market for the oil and gas. Unless the casing is well seated and proper connections installed, the oil and gas may force itself up between the casing and the walls of the hole for a distance and then divert into porous formations. Eventually it may break through cracks or crevices and escape at the surface from seeps or vents several hundred feet from the well. There is no way to estimate how far this oil or gas has migrated from the original source and what amount has been absorbed by

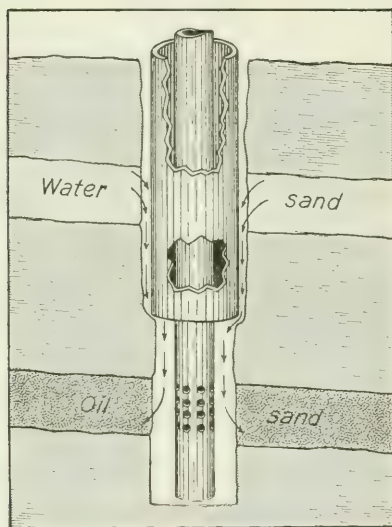


FIGURE 28.—Sketch showing entrance of oil sand from imperfect seating of casing and lack of cement around bottom of outer casing. After Bull. 82, California State Mining Bureau, p. 12.

porous formations. Where wells are cased unsystematically, or where the upper oil or gas can escape to porous sands with less rock pressure the opportunity for loss is great.

A gas well in northern Louisiana was a good example of such a waste. The well blew millions of cubic feet of gas into the air through the casing, but so great was the pressure that several small craters were formed surrounding the well, some being as much as 800 feet from it. (See Plate XX, p. 152.) The gas escaped laterally through porous formations and would work up vertically through joints or cracks to a porous bed, then horizontally to another crack, and so on until reaching the surface.

There it finally escaped, forming small craters. It is reasonable to assume that untold quantities were imprisoned in the underground strata in irrecoverable places and never reached the surface.

Wagy⁹⁵ described the cause of the trouble as follows:

The operators finished drilling this well about August, 1918; and the gas started blowing around the outside of the casing. An attempt was made to stop this by placing concrete around the casing at the top of the hole; 100 sacks of cement is said to have been used. The gas did not stop blowing, and finally blew out such a cavity that the concrete block and 10-inch casing dropped out of sight. While attempting to find the casing again, the well went "wild"

⁹⁵ Wagy, E. W., Personal communication.

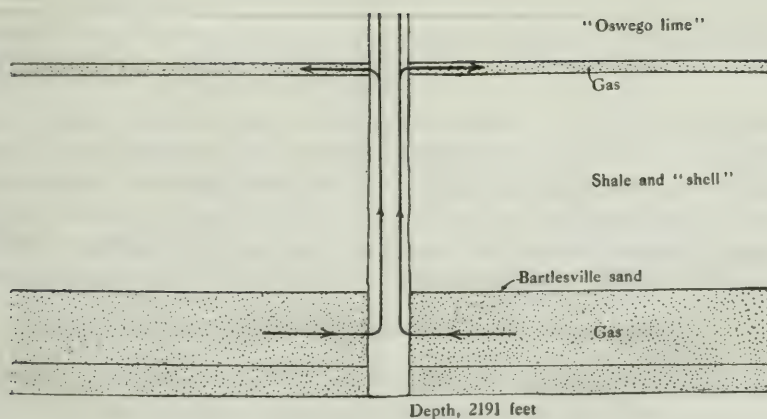


DIAGRAM OF WELL IN OSAGE COUNTY, OKLA.

Shows condition of well and way in which gas escaped to surface. Well was completed May 8, 1914, with an open flow estimated at 22,000,000 cubic feet. When shut in the gas cut under each string of casing, which was landed in shale, and escaped into the other sands. Gas had reached the surface as far as 600 feet from the well, and for a radius of 300 feet was issuing from the ground in large volume, when inspected on August 11, 1915.

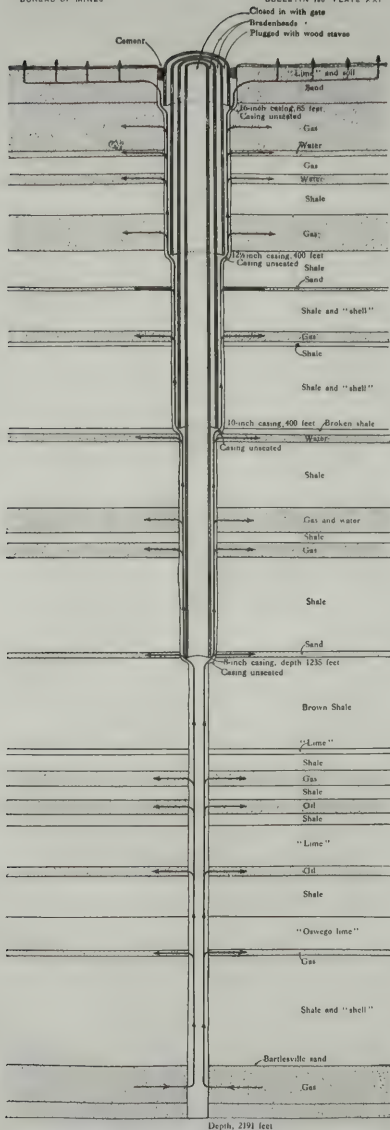


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about November, 1918, and has been blowing wild ever since. A crater was then immediately formed and a number of other gas blowouts occurred all around this well for a distance of about 800 feet. It is said that the rock pressure on the surrounding wells was reduced perceptibly after this well had been blowing for some time. At the time we were there (March, 1919) there were a number of very shallow pools of water standing all around in the neighborhood and numerous bubbles of gas were visible over very large areas.

LOSSES DUE TO PERFORATING ALL SANDS.

If gas will migrate laterally 800 feet as described above and force its way vertically through several hundred feet of formation, some idea may be gained as to the harm that will result from exposing

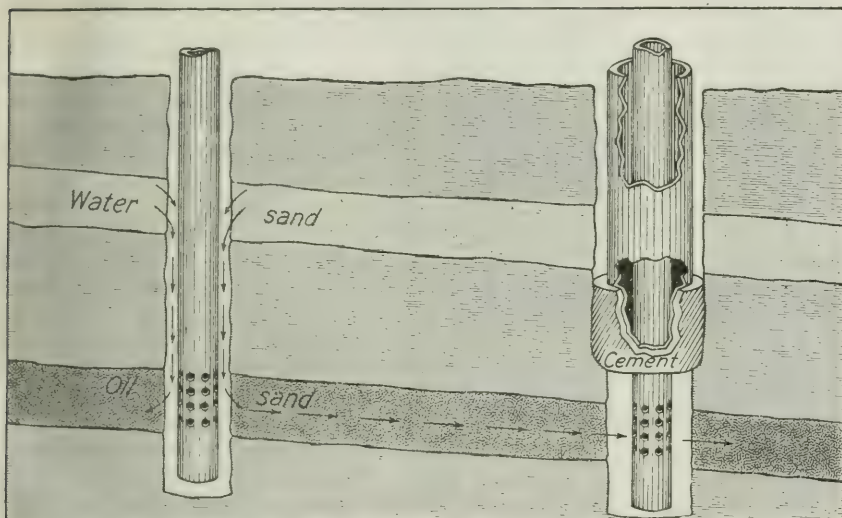


FIGURE 29.—Sketch showing entrance of water into oil sand and its migration to a properly drilled well, from the use of only one string of casing in first well. After Bull. 82, California State Mining Bureau, p. 13.

oil and gas to porous formations underground. In California, particularly, the tendency is for the operators to perforate opposite several sands, although they are not certain that all of them are oil and gas bearing. Much oil and gas is under enormous rock pressure, and undoubtedly the perforation of all sands causes a large underground waste. This condition is brought out in Plate XXI.

LOSSES CAUSED BY NOT KNOWING PRODUCING ZONE.

Tremendous losses may be caused by the operator's failing to realize the exact horizon that affords production. Often careful study by the petroleum engineer will show the depth at which a well would be expected to encounter the producing zone, and the foreman would thus be prepared to handle the well in a proper

manner. In wildcat wells the producing horizon may not be known and in a rotary well a productive horizon may be overlooked. The same thing may happen in a cable-tool well where the hole is full of water and the sands are not tested by bailing.

The Standard Oil Co.'s Hay well, No. 7, in section 36, township 30 south, range 23 east, Elk Hills district, California, showed the possibilities of casing off an oil or gas sand when drilling with a hole full of fluid in an area where the location of the productive sands was not known. The following quotation from the Standard Oil Bul-

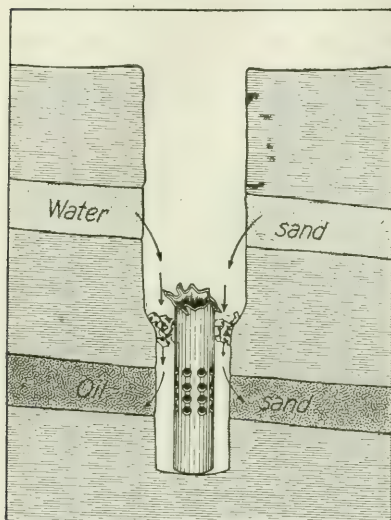


FIGURE 30.—Sketch showing entrance of water into oil sand from withdrawal of casing from an abandoned well without placing a plug between oil and water sands. After Bull. 82, California State Mining Bureau, p. 13.

letin⁹⁶ shows that a gas sand with an estimated initial flow of 100,000,000 cubic feet per day was found really by accident:

The well was drilling with a rotary at 2,135 feet in 10-inch casing, the 12½ and 10 inch strings of casing having been landed, when what appeared to be water sand was encountered. To test this sand for water the mud was bailed out to relieve the pressure and allow any water present to accumulate in the hole. During the course of bailing the well blew out and the enormous flow of gas began. The top of the 12½-inch casing was equipped with a heavy gate valve and a 6-inch flow line, which extended to the side of the derrick. The drilling crew attempted to get the well under control by closing the 12½-inch gate valve, but the shale and sharp sand carried by the stream of gas cut out the seat of the valve while it was being closed. This gate having failed, there was no alternative

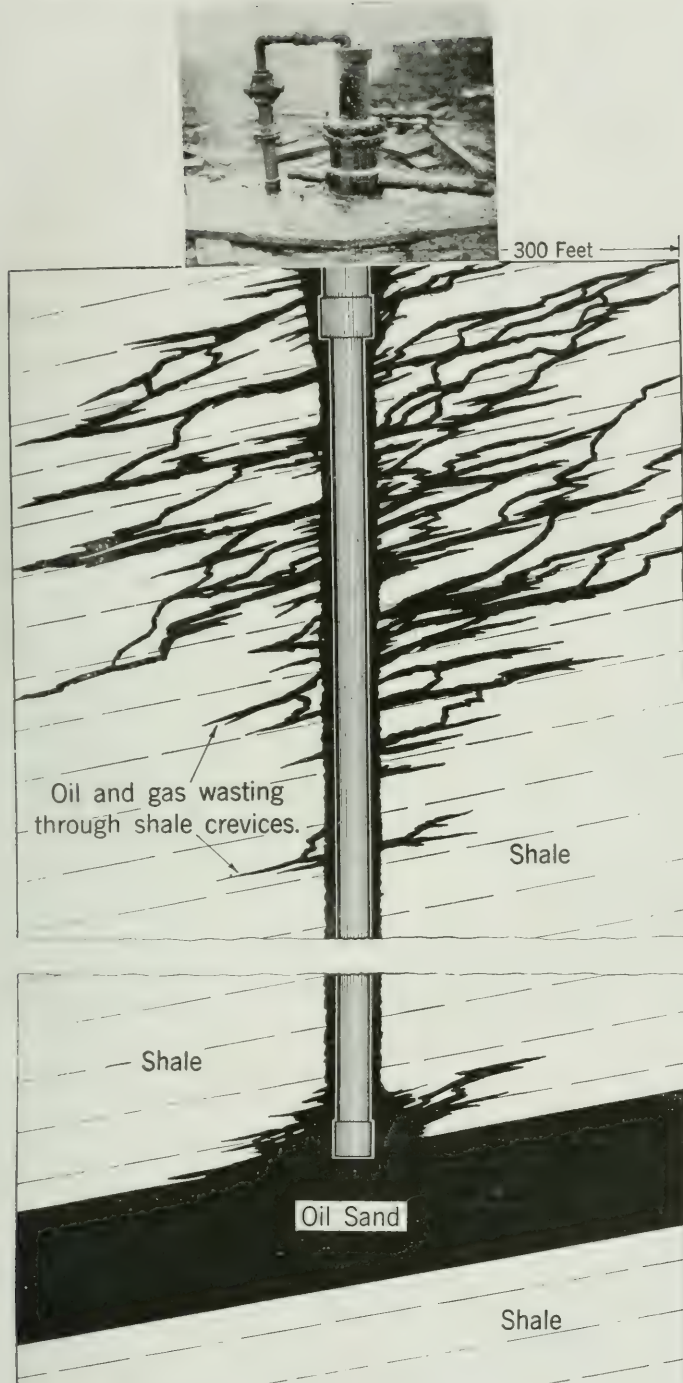
to letting the well blow until more fittings could be attached. After blowing for an hour, the drillers said that the 6-inch flow line became red hot for 2 feet at its end, due to the friction of the shale and sand on the pipe, and ignited the enormous stream of gas.

This well had an estimated flow of 100,000,000 cubic feet of gas per day, but did not show signs of oil or gas until the well was bailed for a test. If the sand had not been tested it is likely that this big gas-producing sand would have been cased off.

LOSSES CAUSED BY IMPROPER DRILLING METHODS.

Losses are caused by improper drilling methods which may result in the oil or gas escaping to overlying porous formations or to the

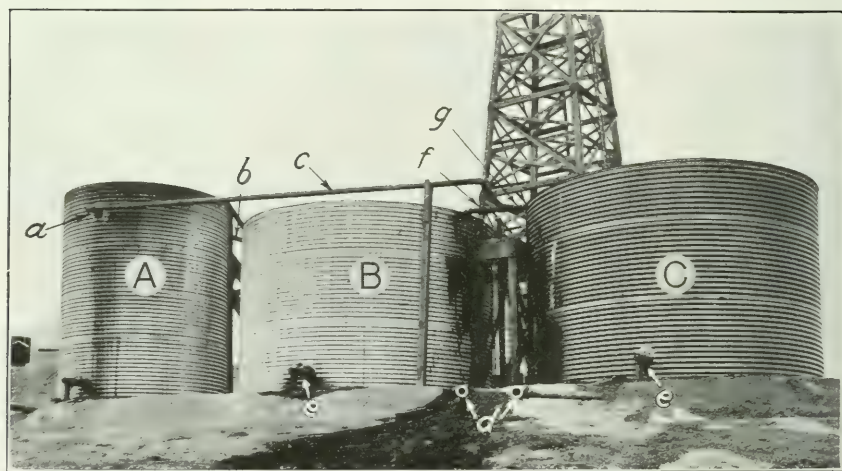
⁹⁶ Midway's midnight sun: Standard Oil Bulletin, August, 1919, pp. 11-13.



SKETCH TO SHOW OIL ESCAPING UP THE SIDE OF CASING AND INTO FORMATION FINALLY REACHING THE SURFACE.

In the territory where this picture was taken oil was escaping 300 feet from the well.

(After F. B. Tough and B. H. Scott.)



TANKS USED FOR GAGING OIL AND WATER BY THE SHELL CO. OF CALIFORNIA,
OILFIELD, CALIFORNIA.

surface. In one field where the wells are flowing against back pressure a well in which no cement was used and a poor casing seat permitted the oil and gas to escape to the surface between the casing and wall of the hole as shown in Plate XXII. The casing shoe was landed without cementing and much oil and gas escaped to the surface, somewhat as sketched in Plate XXII. The oil not only escaped around the well as shown in the photograph, but worked horizontally into the more porous beds and cracks, thence vertically through crevices to another porous bed, thence horizontally, and so on until it reached the surface. In some places oil was flowing and gas bubbling in pools 300 feet away from the well.

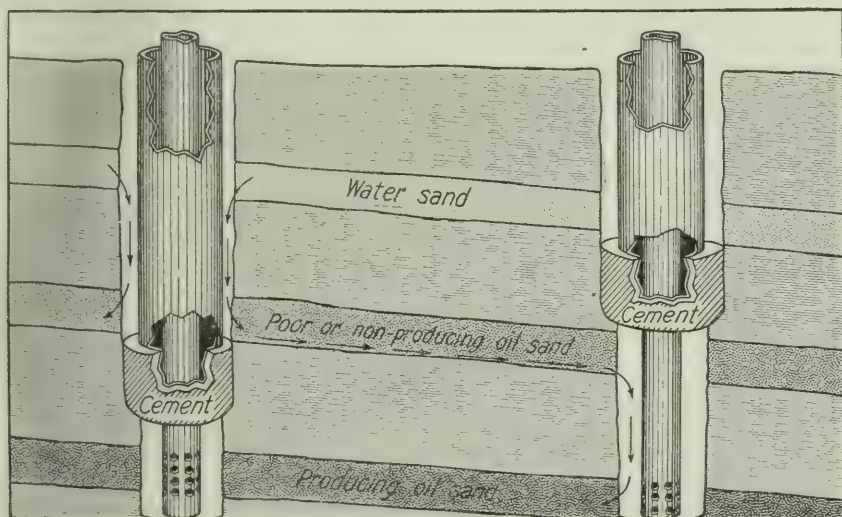


FIGURE 31.—Sketch showing entrance of water from lack of uniformity of distance of shut-off below water sands when two wells penetrate the same strata. If there were only one well, either one would probably be in good condition. After Bull. 82, California State Mining Bureau, p. 14.

If there is sufficient pressure to force the oil horizontally along porous beds and then vertically through cracks in the formation for several hundred feet, the amount of oil that has been dissipated into the porous formations must be enormous.

LOSSES IN DRILLING THROUGH WORKABLE COAL BEDS.

The question of protecting coal mines from escaping natural gas where oil or gas wells were sunk through the workable coal beds of West Virginia, Illinois, Pennsylvania, Indiana, Ohio, and other States, was taken up in a conference in Pittsburgh, Pa., February, 1913. At this conference, which was brought about by the Bureau of Mines, were present members of the bureau, State geologists, mine

inspectors, coal operators, and oil and gas operators from the States interested. The papers read and results of this conference are recorded in Bulletin 65,⁹⁷ of the Bureau of Mines, to which the reader is referred for further details.

The petroleum engineer should consider this subject from the standpoint of waste of oil and gas as well as protection to the mines. The method of casing, the amount of cement to be used, the size of the pillar to be left in the mine, and the proper plugging of wells upon abandonment are points which he should consider when the

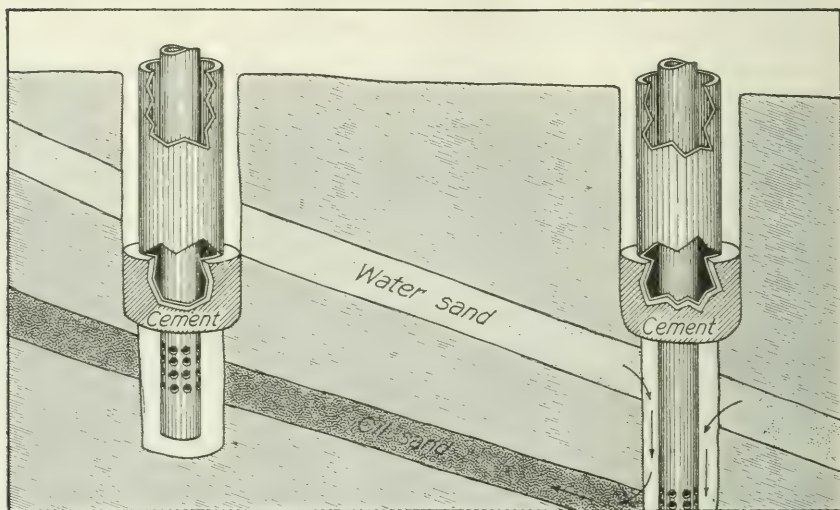


FIGURE 32.—Sketch showing entrance of water because shut-off was made at the same depth in two wells without consideration of the fact that strata most frequently do not lie parallel to the ground surface. After Bull. 82, California State Mining Bureau, p. 14.

wells are sunk through either present or future workable coal beds or other mines.

OIL AND GAS SANDS—LOCATION OF PRODUCTIVE SANDS, THEIR THICKNESS AND QUALITY OF OIL.

LOCATION OF PRODUCING AND NONPRODUCING SANDS.

The loss attendant to exposing all sands in the oil zone of a producing well is discussed on page 163. This emphasizes the need for the engineer to locate the producing and nonproducing sands and thus avoid serious losses. By watching the fluid in the ditch of a rotary, and the dumpings from the bailer, a film or scum of oil or gas bubbles

⁹⁷ Rice, G. S., Hood, O. P., and others, Oil and gas wells through workable coal beds, papers and discussions, 1913, 101 pp.

may give some hint as to the contents of a sand. Testing a sample of sand from a drilling well with chloroform (see p. 24) is better than no evidence at all, but a bailing or pumping test is much more satisfactory. (See "Collection of samples," p. 20.) It may not be possible to test each sand immediately, but records of old tests should be assembled and additional tests made from time to time until bailing or pumping tests have been made on each sand in the oil and gas horizon.

When for any reason a well is held up at an untested zone, a test should be made if practicable. For example, the casing may freeze halfway between the water shut-off point and the proposed bottom

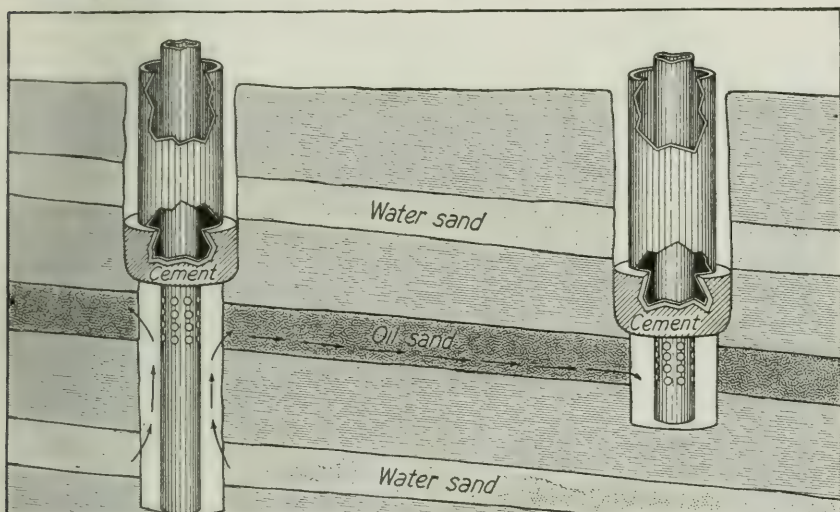


FIGURE 33.—Sketch showing entrance of water into a properly drilled well because another well drilled into a water-bearing sand below the oil sand, but did not plug the lower part of the hole. After Bull. 82, California State Mining Bureau, p. 15.

of the hole. If the decision is to perforate the frozen casing and deepen, the well might be deepened first and the lower sands tested one at a time, thus giving a good idea of their contents, before perforating the frozen pipe opposite the upper sands. On the other hand, the upper sands might be tested by perforating the casing before deepening.

The upper part of the oil zone below the water shut-off point may be tested by deepening in successive stages and testing each porous formation as drilling progresses. In wells where a string of blank pipe is landed on bottom, then one sand at a time may be perforated and tested. A packer on the tubing may be set below the upper oil and gas sands of a producing well to fill the annular space between the tubing and casing or wall of the hole while testing out the lower sands. In doing this care must be taken to prevent the

packer sticking when it is to be pulled. The method of perforating pipe for a test is not always satisfactory, because in drilling the mud may have partly sealed off the sand.

THICKNESS OF SAND AND PRODUCTIVITY.

The depths to top and bottom of a productive sand should be carefully measured, thus giving its thickness. (See method for "stringing in" with sand line (pp. 192 and 193). A study should be made of the relationship between thickness of the sand and ultimate production per acre. In studying the productivity of a sand of varying thickness account must be taken of the fact that different

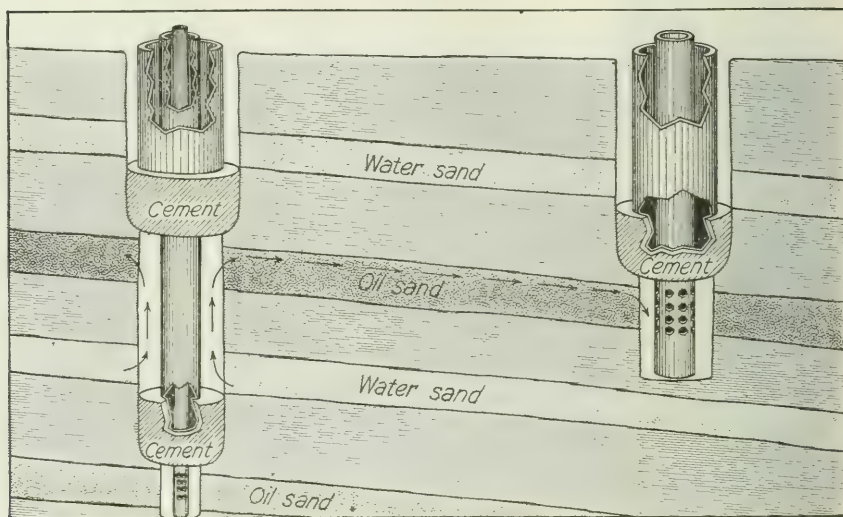


FIGURE 34.—Sketch showing entrance of water into a properly drilled well because a neighboring well entered a deeper oil sand without inserting an extra string of casing to protect the first sand. After Bull. 82, California State Mining Bureau, p. 15.

parts of the same sand may have varying factors of productivity, perhaps from change in porosity or from other causes.

With a large gas pressure an enormous amount of oil may come from a few feet of sand. Some wells drilled only 2 or 3 feet into the oil sand have made a thousand or more barrels of oil per day. Where there are several producing zones separated by a few feet of shale, the greater part of the oil probably comes from only one or two zones. Furthermore, in some fields where there is supposed to be one producing sand, 50 to 75 feet thick, very likely only a small part of this sand furnishes the oil. The producing parts of this thick sand are probably separated by fine-grained tight streaks or layers firmly cemented with silica, or limy streaks, or even thin

breaks of shale not detected by the drill. Therefore, if a well has several sands logged as oil bearing, probably not all of these are oil producing, and where one sand is logged 50 to 75 feet thick only a part of this may be productive. If this is true, the same sand may contain more than one grade of oil, and with several producing sands each sand may contain a slightly different grade of oil. This is discussed later. The lithology of the sand should be studied in conjunction with its productivity. Perhaps this study will point out which parts of the sand need to be shot, if shooting is necessary.

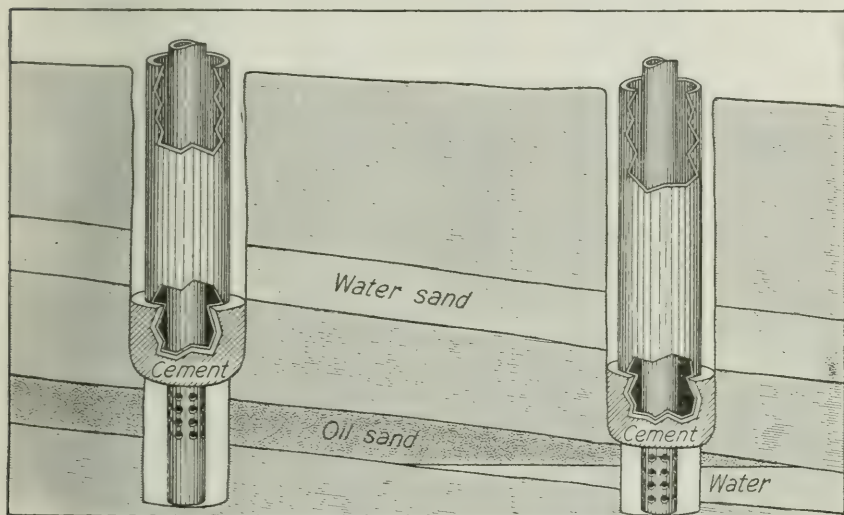


FIGURE 35.—Sketch showing presence of edge water due to a natural condition. Many oil sands when followed far enough down the dip are found to contain only water. As oil is removed from above, water follows it up along the stratum. After Bull. 82, California State Mining Bureau, p. 16.

DISCOVERY OF NEW OIL ZONE.

In drilling a well the likelihood of discovering a new productive oil sand overlooked in other wells should be considered. Such a thing is quite possible where the wells have been drilled with the hole full of water and mud, as this may preclude any showing on the ditch. In a new field the operators are usually looking for the big producing sand. Oil may show in the ditch or on the fluid from the bailer after it has been run to bottom, but if the well does not flow the sand may be passed by without testing.

The proper test is to bail the well down and bring the oil into the hole. Swabbing and shooting may accomplish the same result. The driller will readily understand why the oil does not come into the hole when it is explained to him that in a hole filled with 2,000 feet of water the outward pressure at the bottom is at least 868 pounds

per square inch, and if the fluid carries mud, the pressure is greater in proportion to its specific gravity. Obviously the oil or gas can not enter the hole if the pressure of the fluid is greater than the rock

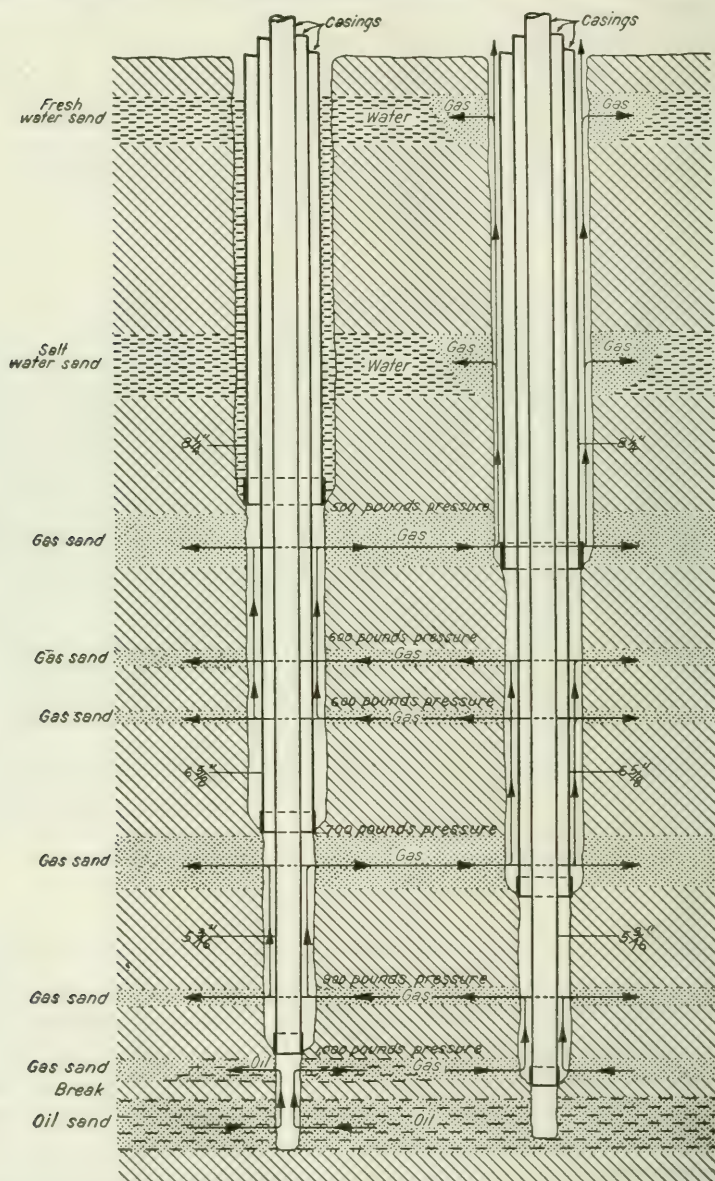


FIGURE 36.—Generalized sketch showing unsystematic casing of wells. Gas pressure greater than water pressure. After Bull. 134, Bureau of Mines, p. 38.

pressure. The rock pressure of a district is usually less than the hydrostatic head, and is always less after the first wells have depleted the pressure.

In parts of the Mid-Continent, Lima-Indiana, and other fields, a well will not show any appreciable production until after it has been shot. In such districts the upper possible producing zones should be shot and tested, unless this has already been done. This may result in wells capable of producing 50 barrels of oil a day.

Possibly all the wells on a property have cased off a good oil sand. Its discovery would increase the value of the property by many thousands of dollars. Given a uniform shut-off on all wells and no information of tests on the sands above the shut-off, the engineer should see that these upper horizons are tested. Such a test may be made satisfactorily on a drilling well. In fact, several upper sands have been discovered accidentally when ripping the casing to reclaim the pipe upon abandonment.

A concrete example of locating additional producing sands by detailed study of underground conditions is shown by figure 37. The well had been drilled to 1,630 feet, but made water at that depth; it was proposed to cement the casing several feet deeper and drill into the lower oil sands. Study of neighboring wells indicated that the upper oil sands of this well should be productive.

A review of the history, as shown graphically on the left-hand side of figure 37, will bring the conditions out more clearly. The 12½-inch casing was cemented at 1,214 feet, after which the well was deepened

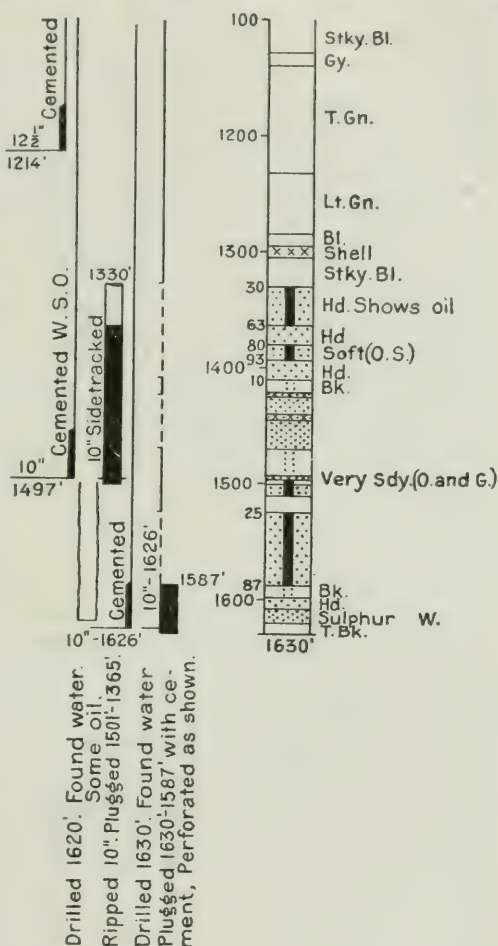


FIGURE 37.—Sketch showing how upper oil sands were passed by. Following underground study, the casing opposite the upper sands was perforated, resulting in a well making 40 barrels of oil per day. For legend of formations, see figure 4.

to 1,497 feet, and the 10-inch casing landed and cemented at that depth. A pocket was drilled and the bailing tests showed that the 10-inch casing successfully excluded all top water from the hole. The well was next deepened to 1,620 feet, when "sulphur water" was noticed. Extensive bailing tests showed that the well made about 200 barrels of water and a small quantity of oil per 24 hours. The operators decided to pull the 10-inch casing and land it below the water sand at 1,610 feet. Accordingly, the 10-inch pipe was ripped and the hole plugged from 1,501 feet to 1,365 feet with cement, brick, and rock. As only 1,330 feet of casing could be pulled, the pipe from 1,330 feet to 1,497 feet was sidetracked. Then the well was deepened to 1,626 feet, and the 10-inch casing landed and cemented at that depth. The cement was allowed to set. A pocket was drilled to 1,630 feet, and bailing tests showed the well would make about 50 barrels of water and some oil in 24 hours.

The detailed underground work was sufficiently advanced at this time to indicate, by a study of adjoining wells, that some of the sands between 1,330 feet and 1,587 feet were productive in neighboring wells. In order to test these upper sands the well was plugged from 1,630 feet to 1,587 feet with cement, and the casing perforated from 1,330 to 1,410, 1,423 to 1,470, and 1,529 to 1,580 feet—that is, opposite the sands. The well then produced 40 barrels of oil, gravity 25.3° B., daily, and no water.

The work on this well indicated five things:

1. After landing the 12½-inch casing the well should have been deepened by stages and the sands tested from 1,330 to 1,497 feet.

2. Each sand should have been tested after drilling below the bottom of the 10-inch casing at 1,497 feet.

3. The cement placed behind the 10-inch casing when landed at 1,626 feet confined the water to its own sand and prevented it from working up behind the casing into the overlying oil sands, as the well made no water when the 10-inch casing was perforated.

4. A producing well was brought in at small expense because of the underground study, which indicates the value of such work. To have cemented another string of casing below 1,630 feet and deepened for production from the lower sands would have made an expensive redrilling job costing several thousand dollars, while the plugging and perforating was accomplished in a short while and for a nominal sum.

5. The upper sands were found to be commercially productive, although the showings on the ditch evidently did not warrant a test on these sands when passing through them.

The possibilities of obtaining production by perforating the casing opposite upper oil sands cased off in the original drilling is

further demonstrated by three examples cited by Van der Leek.⁹² After perforating the casing opposite the upper oil sands, one well came in making 80 barrels of oil per day and 1 per cent water, in another the production increased from 10 of oil per day to 150 barrels, and a third came in making 200 barrels of oil daily and no water.

QUALITY OF OIL.

A study of the quality of oil in a well producing from more than one sand, or even one thick sand, may show that two or more grades of oil are being produced. Gravity tests may serve as a guide to the quality of the various oils, but preferably chemical tests should be run to determine the character of the upper and lower oils, if there be both. The operator may get a high price for a certain grade of oil and desire to produce that grade only. It is necessary to know the exact location of the perforations in the casing. In doing comparative work of this sort, the fact must be borne in mind that the gasoline content and gravity of an oil varies, depending upon the method of production—that is, whether the well is flowing into a trap where the lighter products do not escape, or whether the well flows into an open sump where the various products are exposed to evaporation by wind and heat.

The following concrete case demonstrates the possibility of detecting two grades of oil in the same well. In this particular well, the upper sand directly below the water shut-off point contained an oil of about 20° B. gravity, and the lower sands contained oil of about 30° B. gravity. The casing was perforated opposite all sands. In a test, the heavy oil was shut off by placing a packer on the tubing between the heavy and light oil sands. The well would then produce 250 barrels per day of light oil from the lower sands. When no packer was used, it was possible to pump about 425 barrels of heavy oil, even though the pump was placed near the bottom of the hole. The fluid level of the heavy oil stood about 400 feet from the surface, but no data were available on the fluid level of the light oil.

The heavy oil contained practically no gasoline, whereas the oil from the lower sand yielded about 12 per cent gasoline in an ordinary steam still. The company was in need of the light oil, and accordingly set a packer below the heavy oil and produced the higher grade oil.

⁹² Van der Leek, Lawrence, Perforating casing for the purpose of producing from or testing undeveloped formations: Advance Chapter, Fourth Annual Report of the State Oil and Gas Supervisor, California State Mining Bureau, Bull. June, 1919, pp. 7-8.

DISCOVERY OF DEEPER OIL SAND.

If no deep test wells have been drilled in an area, such a test is usually worth while. On account of the expense involved, the test should be preceded by a careful and detailed study of the geologic structure. The engineer should study neighboring properties, and by use of geologic maps prepared from well logs and other data, determine whether a deep test well is advisable. If the deeper beds outcrop at the surface so that they can be examined, an areal geologic cross section can be made of the exposed beds and estimates made of the probable depth to which it would be necessary to drill.

There may be good chances for striking a deep oil sand, known to be productive in adjacent fields at shallower depths. A careful geological survey is the determining feature of this possibility.

WELL DEPTHS.

The operator is anxious, of course, to drill as deeply as possible to get the production from the lowest sand. By use of his cross sections and data, the engineer can predict with accuracy in a developed field just where to stop drilling. He can offer valuable advice on the number of strings of casing needed and their length and where they should be landed. The depth of troublesome drilling formations can be forecasted. In this, he should be certain the data are complete enough to warrant such predictions.

In an area known to have bottom water or water in the base of an oil sand, one important consideration is how far the well can be drilled below the marker or key bed without encountering this water. The location of bottom water can be determined in a new territory only by drilling into it. When determining its location, drilling should proceed cautiously, with bailing tests every time a new sand is encountered. After locating the water, a sample should be taken for chemical analysis and the bottom of the hole plugged with cement and bailed to see that the plug does not leak.

In a developed field, cross sections, peg models and structure contour maps are of great value in determining well depths. The location of bottom water is often a matter of elimination. First consider the wells that are drilled shallowest stratigraphically and are free from water, then select wells drilled to lower horizons; finally it will be noted that any well drilled below a certain horizon shows bottom water. For example, wells drilled to 400 feet below the marker had no water, but wells drilled 410 feet below the marker made a large amount of water. Again, the well histories may show that some of the wells drilled below the 400-foot point made water, which was shut off when the well was plugged back above that point.

Or perhaps in one or two wells the water was not shut off. This might be due to careless plugging, but if the evidence indicates a good cementing job, then possibly the water string leaks and middle or edge water is coming into these wells.

In a study of bottom waters the condition of the water string should always be considered. It should be known whether the tests showed the water string to be tight and just how these tests were made. A mere statement "Job O. K." does not suffice. The important feature is to know that an actual bailing test was made, and, if so, the results.

In studying the depths of the holes and of the tops of plugs below the markers, it may be found that some wells can be drilled deeper with safety and will thus open up another productive oil sand. From a comparison of yields and gravities of oil in the shallowest wells, stratigraphically, with those of oil from the deeper wells, one may learn the productivity of the lower horizons, the gasoline content of their oil, and that of the natural gas produced with the oil. In line wells, particularly, the operator should deepen in order to withdraw his share of production from the lower horizon.

If the engineer has located a sand with a certain quality of oil, which the company desires for its high gasoline content or other value, he can advise the superintendent just how deep to drill and what sands to perforate in order to get the desired grade of oil.

NEW WELL LOCATIONS AND EXTENSION OF THE FIELD.

In selecting locations of future wells sites can be chosen which will be most likely to give the greatest yields per acre or the most information as to the future of the pool. By the use of cross sections and structure contour maps the number of dry holes will be lessened and tight parts of the sand, which will furnish small producers, largely avoided, as well as parts which yield gas only. The underground contour map, when properly worked up, should indicate the edge-water line, if edge water is present; thus sites can be selected which will avoid drilling into water.

In studying the possible extension of a field, the surface structure map as well as the underground structure contour map should be used (see pp. 46 to 49), as the general underground structure will, in many places, be indicated by the areal structure. In selecting wells based on structure maps the operator is drilling less at random and has some definite reason for drilling a well in a certain location.

The manner of accumulation of oil and gas varies in different fields, but often production extends farther down on gently dipping than on steeply tilted beds. Production also often extends farther down the longer axes of the structures. As a general rule edge water occurs higher up on the steeply dipping beds. (See fig. 17, p. 80.)

It is also noticeable that where there is a general gentle dip in one direction and a reverse dip caused by an anticlinal fold, then production often extends farther down the normal dip. These factors are variable and merely suggestive. However, they serve to point out that the engineer should consider the manner of accumulation in the area and its relation to folding and faulting when determining locations of new wells and the possible extension of the pool. Contour maps are a valuable guide in avoiding synclines and places least favorable for accumulation.

In considering the possible extension of an oil or gas field the engineer should take into account primarily the production of adjoining wells. In testing an extension far out on an anticline, or in testing an undeveloped structure, he should be guided by the gathering ground over which the oil or gas may accumulate. Other important factors are whether the producing sand is pinching out in that direction, the association of a shale that will secrete oil, and the probable depth to oil-bearing sands.

Comparison of the production records with the structure maps aids in determining the most productive undrilled areas. This is illustrated in figure 38.⁹⁹

The writer suggests that the production figures be shown as ultimate production in barrels per acre. Similar figures could be prepared for each tract to show the average initial production of the wells or the production to date of each well, but the ultimate production per acre takes account of both these factors. In figure 38 the northeast quarter of section 1 has a total production of approximately 35,000 barrels per acre, excluding the nonproductive acres. The operator would readily see that he would get a much larger well in this quarter section than in the southwest quarter of section 31, where the total production is 3,500 barrels per acre. He would also see that the contours show steeply dipping beds in the southwest quarter of the southeast quarter of section 36, and that in this sixteenth part of section 36 there are a number of abandoned wells. Only a small production or a dry hole would be obtained in that area.

FUTURE WELL PRODUCTION.

No close estimate can be made of the future value of any producing property without records of the past production of the different wells, but with such figures available an intelligent estimate can be prepared. Besides the records are needed to show the probable future production of each well. Other uses of individual well production records are covered in more detail on page 17.

⁹⁹ See Beal, C. H., The decline and ultimate production of oil wells, with notes on the valuation of oil properties: Bull. 177, Bureau of Mines, 1919, p. 17.

The engineer has compiled and collected the data on individual well productions and is the logical man to prepare the estimates of future production. He is also familiar with the water possibilities, the dissipation of gas, and other factors which will affect future and ultimate production.

Realizing the value of knowing the future production of oil and gas wells, the Bureau of Mines has made a comprehensive study of

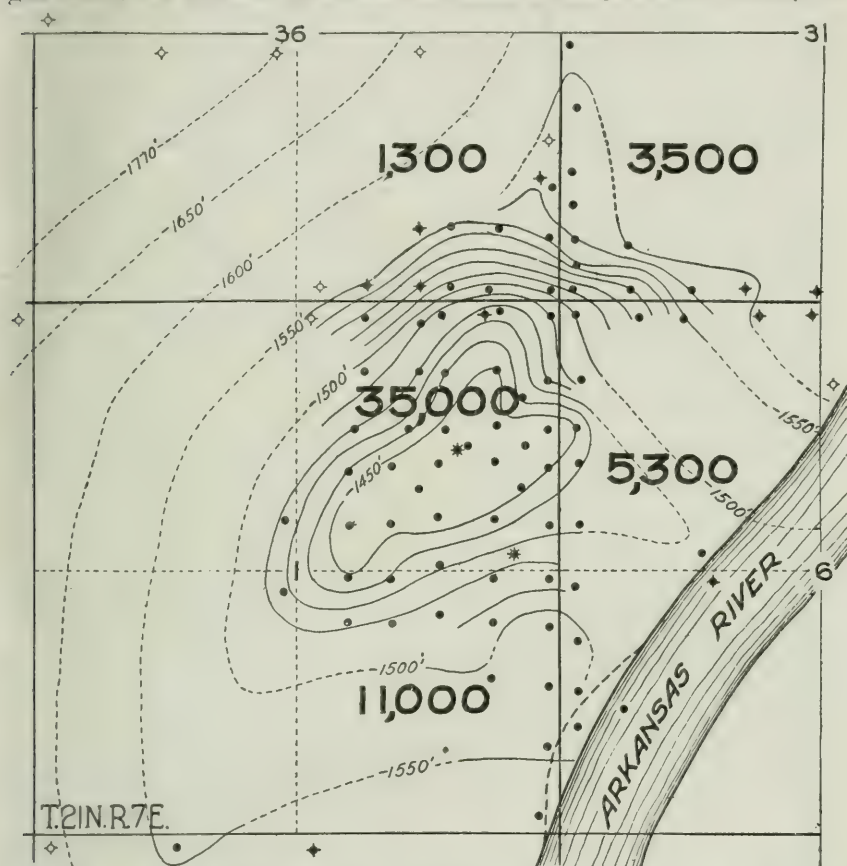


FIGURE 38.—Sketch showing the relation between total production per acre (in barrels) and geologic structure in the Boston pool, Oklahoma. After Carl H. Beal.

means for more accurately determining the valuation of oil properties. The Internal Revenue Bureau of the Treasury Department has adopted the method suggested by the bureau as a basis for determining an equitable tax on oil properties. The work was based on the individual production per well, or rather on an average production per well on a property. The more progressive oil companies of the United States are coming to realize the value of knowing the estimated future production of each well. This subject has been well

covered in standard publications¹⁰⁰ and it is not necessary to describe it in this bulletin.

GAGING OF OIL WELLS.

IMPORTANCE OF GAGING.

Oil-field operators are appreciating more and more the importance of keeping daily records of individual well production. The value of a property depends on its future production, and in order to determine what a well may do in the future a knowledge of its past production of oil and water and the general condition of the hole is necessary. The use of individual well-production records will show which wells will pay to repair in case of bad pipe, which wells pay to clean out, whether the abandoning of a well would be more profitable than to operate it, and the probable life of the wells.

The increase or decrease in oil production revealed by comparison of past and present records may answer the questions, Does it pay to shoot the wells? Is gas pumping beneficial? Does it pay to pump full time or part time, and which production foreman or farm boss is most efficient? The records are helpful in the spacing of wells and in directing the drilling program. They also are used in a study of water problems; up-to-date records point out daily which wells are low producers and need to be worked on. (See p. 17.)

The daily water and emulsion tests have been used by one company to tell when to pull a well. When any well showed an unusually high emulsion percentage the well gang immediately "pulled" the well to replace cut valves. High emulsion percentages served as a true guide for telling when to replace the valves, and on this property practically never failed.

The value of production records has been emphasized by the Internal Revenue Bureau of the Treasury Department adopting well production records as a basis for taxation purposes. Investors, directors, and engineers are coming to realize more and more that our future supply of petroleum is limited while consumption is steadily increading, all of which leads toward conservation and a maximum recovery of the oil underground. In order to determine the future production of a property, as previously stated, it is necessary to know the past and present production of each well. This same information

¹⁰⁰ Lewis, J. O., and Beal, C. H., Some new methods for estimating the future production of oil wells: *Trans. Am. Inst. Min. Eng.*, vol. 59, 1918, pp. 492-520; Beal, C. H., The decline and ultimate production of oil wells, with notes on the valuation of oil properties: *Bull. 177, Bureau of Mines*, 1919, 215 pp.; *Manual for the oil and gas industry*: U. S. Treasury Dept., 1919; Beal, C. H., and Nolan, E. D., The application of the law of equal expectations to oil production in California: *Am. Inst. Min. Eng., Bull. 152*, August, 1919, pp. 1237-1245.

is equally important in determining at what rate the oil will be obtained. This is emphasized by Beal.¹

The water production is very important in studying the future life of a field. A well may be declining normally when water will appear and completely cut off production. The effect of water on production is shown in figures 16 (p. 76), 25 (p. 123), and 39. Figure 39 shows that water appeared in a well in February, 1912. The water gradually increased, and by May, 1913, constituted the bulk of the production. From February, 1912, to April, 1913, the oil production was declining at a fairly normal rate, but in May, 1913, the water flooded the well. The oil was not exhausted, as shown by the increase in oil production in 1915 following a partly successful repair job on the well in 1914.

The operator can best detect any increase in water content by adopting means for gaging the oil and water production of a well. In fact, in solving water problems in a field, one of the most important things is to know the oil and water record of each well. If such records are complete, they will show what well first made water, when this water appeared at other wells, what group of wells first made water, and the effect of this water on production—all highly important questions.

Without any production records, such data as possible should be compiled from well histories and from questioning pumpers and other men employed about the lease. However, data collected in such a way are extremely unsatisfactory and often unreliable; they should be confirmed constantly, where possible, by actual measurements.

Where well gaging has not been practiced, immediate steps should be taken to install a system for obtaining individual gages of oil and water of each well at least once in 10 days, if it is not feasible to do so daily. It is necessary that a reliable system be adopted at the very start. Gaging can be done by the pumper at little or no extra cost and the additional office work is negligible in comparison with the value of the results.

One of the big problems in the Mid-Continent district is to find an inexpensive method for determining the oil and water content of a group of producing wells running into a storage tank. This is discussed later.

BARRELS RATHER THAN PER CENT OF WATER SHOULD BE CONSIDERED.

In considering the water conditions of a well, the actual water produced and not the percentage is the most important feature. For illustration, a well producing 50 barrels of fluid daily with a

¹ Beal, C. H., The decline and ultimate production of oil wells, with notes on the valuation of oil properties: Bull. 177, Bureau of Mines, 1919, p. 35.

water content of 20 per cent makes 10 barrels of water a day, which is not serious, whereas a well producing 800 barrels of fluid with a water content of 20 per cent makes 160 barrels of water per day, which is decidedly serious. *Thus, the total barrels of water and not

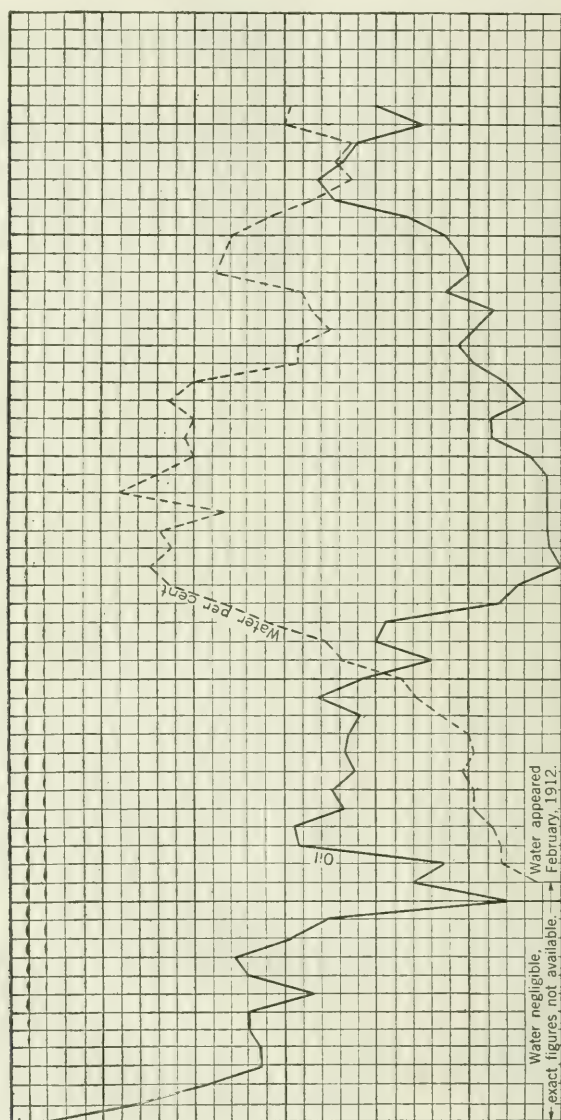


FIGURE 39.—Plot of monthly production of well, showing effect of water upon oil production.

the percentage is important. If the water is not actually measured, at least some kind of measurement should be made of a well's total fluid; from this figure and centrifuge tests of a lead-line sample the total oil and water can be computed.

DEFINITION OF TERMS.

A brief explanation is given here of various terms used in connection with the gaging of wells.

Total fluid is, as its name implies, the total oil, water, emulsion, and B. S. produced by a well.

Gross, piped, or gaged oil is the gross liquid which remains after the fluid has settled and the water drained off, and which is piped to the stock or storage tanks on the property. Gross oil may contain water that refuses to settle out of the oil on standing under ordinary conditions.

Clean or pure oil is the theoretically pure oil which is determined by making a centrifuge test of the gross oil and deducting the water in suspension, emulsion, B. S., and other impurities. Inasmuch as practically all pipe-line companies will accept up to 3 per cent of water in suspension, and as very little oil is totally free of water, the term "pure oil" is a paper term.

Net oil represents the computed volume of the oil after water, emulsion, and other impurities are deducted and after being reduced to an equivalent volume at 60° F. It is a basis or measure of buying and selling oil and is purely a paper figure.

Free water.—When the fluid from an oil well is pumped into a tank or sump, the greater part of the water usually settles out rapidly. This water is termed "free water."

Emulsion usually refers to an intimate physical mixture of oil, air, and water. The water is in such small globules that it is not affected by gravity, and will not settle out of the oil regardless of the time the fluid is allowed to stand. In order to separate the two, expensive dehydration plants are used.

Water in suspension.—The gross oil of some wells holds in suspension a certain proportion of water, which refuses to separate from the oil under ordinary settling conditions. This water is apparently not so intimately associated with the oil and is less difficult to separate out than water in the form of emulsion. Generally speaking, the water in suspension is harder to separate from the heavier oils than from the lighter oils.

B. S., or bottom sediments or bottom settlings, is the sludge that settles out in tank bottoms. This sludge consists of minute shale fragments, mud, sand, and other heavy impurities.

Even in the actual measurement of gross oil and free water account must be taken of the fact that in many crudes some water remains in suspension and does not settle out when allowed to stand for several days. The fluid may appear to be free from water, but a centrifuge test will show differently. As an example, consider a

well making 300 barrels of fluid a day, 20 barrels of which settles out as free water. If a centrifuge test shows that the remaining 280 barrels carries 20 per cent water in suspension, then the well's production would be 224 barrels of clean oil and 76 barrels of water in the 24 hours. Twenty barrels of water may be allowable in some fields, but when a well makes 76 barrels of water in 24 hours it generally needs prompt attention. (For percentage figures on water in suspension see Table 4, p. 188.) Where a centrifuge test is made of a lead-line sample and the total water and clean oil computed from this figure and from the total fluid produced, then the water in suspension and emulsion is of course accounted for.

METHODS OF GAGING.

There are two general methods of gaging—one where the production of oil and water from a well is actually measured for each 24-hour period and another where the 24-hour production is estimated, based upon the production the well makes in a given time. In the last method it is assumed that the well produces at a constant rate.

ACTUAL MEASUREMENT OF OIL AND WATER.

A method used by the Shell Co. of California, Oilfields, Calif., where all oil and water produced by each well is carefully gaged, is as follows:

The receiving or settling tank A (Pl. XXIII, p. 165) is filled to the outlet *a* with water. Any oil and water coming from the lead line *b* into tank A flows through pipe *c* over into the gage tank B, the valve *f* to tank B being open and the valve *g* to tank C being closed. Any sediment coming through the lead line settles into the bottom of tank A (in the newer installations this tank is dispensed with). At the end of 24 hours the inlet valve *g* to tank C is opened and the inlet valve *f* to tank B closed. A gage is made of the total fluid in tank B. A separate drain or "bleeder," *d*, is connected to the bottom of each tank. (In the photograph the drain pipes *d* from the bottom of tanks B and C appear to be connected to the oil outlets *e*, whereas they extend under the bottom of the tanks and are not connected to the oil outlet. Practically all of the oil outlet pipe which connects tanks B and C to the collecting system is covered by earth.) The bleeder to tank B is opened and the water drawn off until oil comes, then the valve is closed and another gage is taken. The difference between the first two gages determines the free water produced in 24 hours; the fluid remaining in the tank is gross oil.

Once every week a centrifuge test of the gross oil is made in order to determine the emulsion, water in suspension, or B. S. that

does not settle out; from the weekly figures a monthly average is computed. Thus, at the end of the month the company has for each well the barrels of gross oil and the barrels of free water produced during that month and the average percentage of water or impurities in the gross oil. From these figures can be computed the total water, the impurities, and actual clean oil produced by each well during the month. The method of computations is discussed under "Accuracy of lead line centrifuge tests" (pp. 187 to 189).

After gaging the gross oil, the oil outlet *e* of tank B may be opened and the gross oil run to the storage tanks or collecting system. This outlet is closed the next morning when the gager or pumper stops at the wells and changes the tanks, that is, one inlet valve is opened to tanks B and C and the other closed. The change can be made oftener than every 24 hours if the 24-hour production is more than the capacity of the gage tank. The gaging and changing of tanks can be done by the pumper, who telephones or sends in daily the measurements to the office, where a clerk converts the feet and inches of oil, as read on the gage stick, into barrels of fluid by means of a table.

As the water in some oils is slow to settle, the oil outlet *e* is about 1 foot above the bottom of the tank, so that any water remaining in suspension in this bottom foot has an extra 48 hours or more in which to settle out. The tables used to convert the readings of the gage stick to barrels of fluid should take account of this fact.

The capacity of the receiving tanks used by the company is generally about 140 barrels, and that of the gage tanks, 250 barrels, the size of the tanks depending on the well production. Evidently the receiving or settling tank does not justify the expense attached to its installation, as the company is abandoning its use. This is brought out by McDuffie.²

Two hundred and fifty barrel tanks, with covers, cost approximately \$230 each, and 140-barrel tanks, without covers, which are used for settling tanks, cost \$140 each. However, we do not approve of the use of these settling tanks, as we believe them to be quite unnecessary—that is, we do all the gaging of the water in the 250's, and if any amount of sand is pumped a small sand-settling device should be provided. In fact, we are now taking out all of the 140-barrel tanks and using them as gage tanks. On an average it costs about \$60 to set up and connect the tanks.

Some companies have two gage tanks of about 200-barrel capacity each at every well. The tanks are used to gage the well production similar to the method described above. There is no receiving tank

² Personal communication from W. C. McDuffie, field superintendent, Shell Co. of California, San Francisco, Calif., Feb. 25, 1919.

and the oil flows directly from the lead line, settling devices, or sump (if the well makes much sand) to the gage tank.

PERIODICAL GAGES BASED UPON PRODUCTION IN A SPECIFIED TIME.

Various methods are used in gaging based upon the general idea of computing a well's production for 24 hours after knowing the amount it makes in a certain length of time. The well's production is assumed to be constant over the 24-hour period. These estimates give surprisingly close data, although when a well flows by heads the results are not so close. If such a method is used, a gage should be taken over as long a period as possible, particularly if a well produces oil and water alternately.

A few of the more common practices in estimating the daily production from the gaged production over a few hours or shorter period are described here.

A 25 to 50 barrel tank may be stationed at a well and an actual gage taken once a week for a definite number of hours. Such a tank could be mounted on wheels and drawn from well to well, although this is inconvenient. From the production made in a given time, the total production per 24 hours is computed. Lead-line samples are also taken to determine the percentage of oil, water, and emulsion in this fluid. The percentage of water and emulsion multiplied by the estimated total fluid gives the production of water and emulsion in barrels, which subtracted from the total fluid gives a figure for the amount of clean oil produced in barrels.

The tank may be so equipped that the water can be drained off; thus, the amount of free water and gross oil made in the given time would be more accurately obtained. Then, centrifuging a sample of the gross oil will show the amount of clean oil and total water and emulsion produced in the specified time of the gage. From such figures, the production in 24 hours can be computed, as on page 187.

At the end of the month the piped oil received at the storage tanks from a number of wells is known. With these weekly gages as a basis, the well's production for the month is established. For example, a sum of the estimated daily production of each well is taken over the month, and the ratio of a well's estimated daily production to this sum multiplied by the total oil received for the month at the storage tanks of the several wells gives approximately the production of the well during that month.

Where production is small, a 5-gallon can is sometimes used; the fluid from the lead line for a certain length of time is caught, measured, and the equivalent production determined for 24 hours,

or the production for 24 hours is computed from the time required to fill the 5-gallon can.

A method of gaging used on the property of the American Petroleum Co., Coalinga, Calif., as described by T. J. Crumpton,³ is summarized as follows:

The wells that make a large amount of water are pumped into a sump. The water is drawn off from near the bottom of the sump through a pipe so regulated as to keep the water level constant. Any oil that comes in flows out through another pipe having its outlet several inches above the top of the water level. The outflowing water as well as the oil is gaged by means of a 5-gallon can measurement which is taken three or four days running and from which an average is drawn. The time taken to fill the 5-gallon can is used as a basis for calculating the well production per 24 hours. The clean oil is determined by computations involving a centrifuge test of the gross or piped oil and the estimated gross oil production in 24 hours.

At some of the wells, this company uses a 50-barrel tank (see fig. 40), from which the water drains out through a pipe at the bottom.

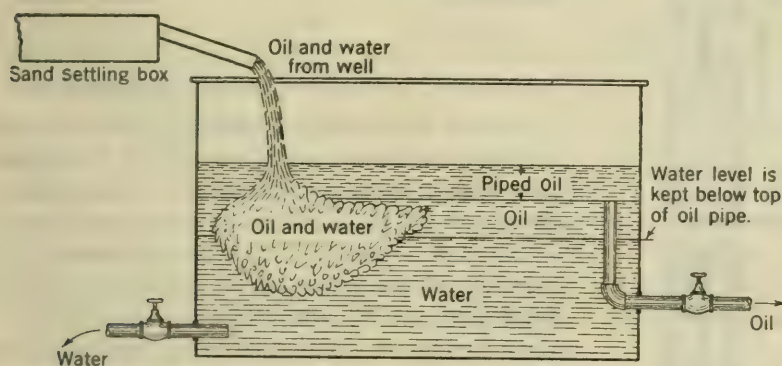


FIGURE 40.—Settling tank placed at oil well by American Petroleum Co., Coalinga, Calif., to separate oil and water, and for gaging gross oil.

An effort is made to regulate the valve at the bottom so that the water drains out at the same rate it is pumped in from the well, the rate of water flow being determined by measuring the time required to fill a 5-gallon can. The gross or piped oil is withdrawn from the tank by means of a pipe whose outlet is several inches above the water level. The oil production can be measured by closing the oil outlet and measuring the amount of oil collecting in this tank in a certain time, as the water level is held constant by means of

³ Crumpton, T. J., Gaging oil and water at well: California Oil World, Apr. 11, 1918, p. 1.

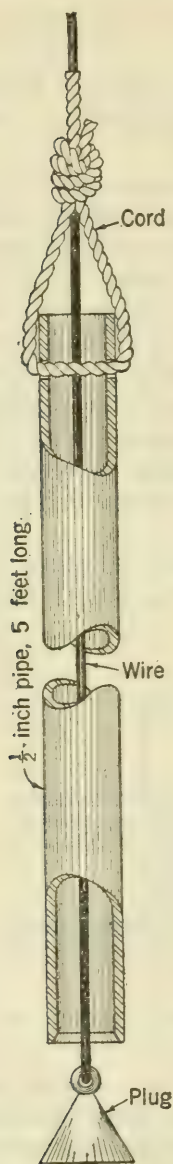


FIGURE 41.—Homemade thief to obtain samples of fluid from a tank. The plug or valve remains open as the thief is lowered slowly to the bottom by the cord. On reaching bottom, the wire is pulled, closing the valve. The thief is withdrawn from the tank by the wire that keeps the valve closed.

the water drain near the bottom of the tank. A centrifuge test is taken of the oil in order to determine the per cent of water or emulsion in the oil. From this percentage figure and the gross oil, the amount of clean oil can be computed.

Where the oil and water are produced at a uniform rate and the well does not flow by heads the well may be gaged by closing both oil and water outlets and measuring the amount of fluid produced in a given time. Then by means of a centrifuge test of a lead-line sample the clean oil and total water production for a given period may be computed.

R. P. McLaughlin⁴ estimated the cost of equipment for this method of gaging as follows:

One 50-barrel galvanized tank (height 4 feet, diameter 9 feet)	\$55.00
Pipe and fittings	12.50
Labor	4.50
Total	72.00

"THIEFING" A SAMPLE OF FLUID FROM GAGE TANK.

Because of the water, emulsion, or B. S. that refuses to settle out of the gross oil it is necessary to make a centrifuge test of a representative sample of the gross oil to determine the amount of impurities present. This sample can be collected by oil samplers or oil thieves, which are listed in many oil-well supply trade catalogues. Most commercial samplers are so designed that they can be tripped at any depth to collect an 8 or 12 ounce sample of the fluid at that depth, the sample being then withdrawn from the tank and emptied into a container. An average sample of the whole tank can be obtained by collecting samples at successive depths and mixing them in a suitable container.

Commercial thieves or samplers cost \$25 to \$50. In gaging oil wells producing 25 to 500 barrels a day, or even more, a homemade device, as shown in figure 41, can be used to "thief" a tank with 4 or 5 feet of fluid in it.

⁴McLaughlin, R. P., Necessity of gaging, California Oil World, Apr. 11, 1918.

The advantage of this particular thief is that when carefully handled it recovers a core sample that should represent an average sample of the fluid in the tank. The thief consists of a one-half inch or five-eighths inch pipe, 4 to 6 feet long, with a wire through the center. The wire is attached to a conical-shaped plug at the base, which serves as a valve. The wire usually bends so that it rubs the inside of the pipe and holds the valve open as the thief is lowered slowly to bottom by means of the cord. When the thief reaches bottom, the operator takes hold of the wire, which closes the valve at the base and releases the cord. Then the thief, containing a core sample of the fluid, is pulled from the tank by the wire. The pull on the wire keeps the valve closed as the thief is withdrawn. The base of the pipe is placed in a bottle or other container and the sample emptied by releasing the pull on the wire.

ACCURACY OF LEAD LINE CENTRIFUGE TESTS.

Centrifuge tests of a lead-line sample to determine the relative amounts of oil, water, and emulsion produced by a well have often proved reliable. In any event, centrifuge tests of a lead line are far better than no water tests. One objection to the use of periodical gaging and lead-line samples is that when a well produces oil and water alternately, the obtaining of an average sample of the well's production is difficult. Again, where a well is flowing by heads, a gage of 1 hour may not give a correct estimate of production per 24 hours. Fortunately, in many wells the rate of oil and water production is fairly constant. Where a sample shows an unusually high percentage of water, a check sample should be taken, as the sampler may have collected the sample just when the well was making mostly water. Where a well makes oil and water at a fairly uniform rate, centrifuge tests of a lead-line sample give a good average.

TABLE 4.—Daily production of well under observation.

July, 1916. Well No. 1. Sec. 15, T. 19 S., R. 15 E.

Gage tank.						Lead line.		
1	2	3	4	5	6	7	8	9
Day.	Gross oil.	Free water.	Water in suspension in gage tank.	Clean oil.	Total water.	Water in lead line.	Clean oil.	Total water.
	Barrels.	Barrels.	Per cent.	Barrels.	Barrels.	Per cent.	Barrels.	Barrels.
1	162.50	10.00	14.4	139	33	24.0	131	41
2	160.00	10.00	16.4	134	36	22.0	133	37
3	160.00	10.00	18.0	131	39	38.0	105	65
4	160.00	10.00	14.0	138	32	20.0	136	34
5	160.00	10.00	13.6	138	32	24.0	129	50
6	160.00	10.00	13.0	139	31	26.0	126	44
7	160.00	10.00	15.0	136	34	19.4	137	33
8	160.00	10.00	16.0	134	36	23.0	131	39
9	160.00	10.00	15.4	135	35	18.0	139	31
10	160.00	10.00	12.8	140	30	20.0	136	34
11	160.00	10.00	12.0	141	29	20.0	136	34
12	157.50	10.00	12.2	138	29	20.1	134	34
13	160.00	10.00	12.2	143	30	20.0	136	34
14	157.50	10.00	12.0	139	29	20.0	134	34
15	157.50	10.00	13.6	135	33	18.0	137	30
16	157.50	10.00	12.4	138	30	18.4	137	31
17	155.00	10.00	22.0	121	44	24.0	125	40
18	157.50	10.00	14.0	135	32	20.0	134	34
19	155.00	10.00	22.0	121	44	22.0	129	36
20	150.00	7.50	a 12.7	131	27	19.0	128	30
21	155.00	7.50	3.4	150	13	16.0	137	26
22	160.00	7.50	15.4	134	33	22.0	131	37
23	157.50	7.50	16.0	132	33	28.0	119	46
24	157.50	10.00	13.0	137	30	18.4	137	31
25	157.50	7.50	18.4	129	37	26.0	122	43
26	157.50	7.50	26.0	117	48	22.2	128	37
27	157.50	7.50	2.8	153	12	26.0	122	43
28	143.25	6.75	14.0	123	27	22.0	117	23
29	155.00	7.50	14.0	133	29	24.0	124	39
30	157.50	7.50	12.1	138	27	18.0	135	30
31	157.50	7.50	12.0	139	26	17.0	137	28
	b 4,885.75	b 281.75	c, d 14.2	b 4,188.56	b 978.94	c, e 21.5	b 4,040.72	b 1,126.78

a Test missing; average of preceding and following day used.

b Total.

c Rough average.

d Av. em. 2.5.

e Av. em. 1.6.

(Signed)

SHELL CO. OF CALIFORNIA.

The reliability and accuracy of lead-line tests were demonstrated by some work of the Shell Co. of California, Oilfields, Calif., several wells being placed under observation over a period of several months. The comparative results are shown in Table 4, which records daily measurements and gages made on the wells. The second column shows the actual daily gage of the piped oil (see pp. 182 and 183 for description of the Shell Co.'s method of gaging), and the third column records the daily gage of free water, the sum of these two columns representing the total fluid produced each day. A thief sample of the gross oil was taken daily to determine the per cent of water in suspension, which is recorded in the fourth column. From this set of figures the amount of clean oil and total water was figured. For example:

162.5×14.4 per cent=23.4 barrels of water in suspension,

162.—23.4 barrels=139.1 barrels of clean oil by actual gage,

10.0+23.4 barrels=33.4 barrels of water (total by actual gage and suspension).

Now—

162.5+10 per cent=172.5=total amount of fluid first day.

172.5×24 per cent=41.4 barrels of total water by centrifuge test.

172.5-41.4 per cent=131.1 barrels of clean oil by centrifuge test.

That is, in actual gaging of the production the results showed 139 barrels of clean oil and 33 barrels of total water against the centrifuge test of 131 barrels of clean oil and 41 barrels of water. The production for the month, however, shows that the results of the lead-line tests were within allowable limits, thus: 4,189 total clean oil by actual measurement, against 4,041 by lead-line centrifuge; 979 total water by actual measurement, against 1,127 by lead line centrifuge.

The decimals were carried in the computations for a check, but not on the typewritten sheets, as they tend to obscure the outstanding features.

PREPARATION OF GAGE TABLE.

A customary practice in measuring the height of the fluid in a tank is for the pumper or gager to drop a wooden measuring stick graduated in feet and inches into the tank. The height of the fluid represents a certain volume dependent on the diameter of the tank.

TABLE 5.—Sample gage table used in converting height of fluid in gage tanks to barrels.

Company

Tank No.

Size of Tank Dia. Height

Capacity of Tank, 250 bbls.

File No.

Sheet No.

Date 192

Strapped by

Computed by

In.	0 feet.	In.	1 foot.	In.	2 feet.	In.	3 feet.	In.	4 feet.
0		0	30.00	0	60.00	0	90.00	0	120.00
1	2.50	1	32.50	1	62.50	1	92.50	1	122.50
2	5.00	2	35.00	2	65.00	2	95.00	2	125.00
3	7.50	3	37.50	3	67.50	3	97.50	3	127.50
4	10.00	4	40.00	4	70.00	4	100.00	4	130.00
5	12.50	5	42.50	5	72.50	5	102.50	5	132.50
6	15.00	6	45.00	6	75.00	6	105.00	6	135.00
7	17.50	7	47.50	7	77.50	7	107.50	7	137.50
8	20.00	8	50.00	8	80.00	8	110.00	8	140.00
9	22.50	9	52.50	9	82.50	9	112.50	9	142.50
10	25.00	10	55.00	10	85.00	10	115.00	10	145.00
11	27.50	11	57.50	11	87.50	11	117.50	11	147.50

In.	5 feet.	In.	6 feet.	In.	7 feet.	In.	8 feet.		
0	150.00	0	180.00	0	210.00	0	240.00		
1	152.50	1	182.50	1	212.50	1	242.50		
2	155.00	2	185.00	2	215.00	2	245.00		
3	157.50	3	187.50	3	217.50	3	247.50		
4	160.00	4	190.00	4	220.00	4	250.00		
5	162.50	5	192.50	5	222.50	5			
6	165.00	6	195.00	6	225.00	6			
7	167.50	7	197.50	7	227.50	7			
8	170.00	8	200.00	8	230.00	8			
9	172.50	9	202.50	9	232.50	9			
10	175.00	10	205.00	10	235.00	10			
11	177.50	11	207.50	11	237.50	11			

Tables (see Table 5) are prepared from which the volume of fluid for a given height can be read directly. These tables are prepared by strapping the tank. Usually the outside circumference of the tank is measured at the top, middle, and bottom of the tank; then allowance is made for the thickness of the tank walls and a table is prepared, in feet and inches, so that with a given height of fluid, the volume in barrels can be read directly. In preparing such a table, account must be taken of any "dead material," such as roof supports, which may take up space inside the tank.

Details for computing a gage table for oil-storage tanks have been covered by Bowie.⁵ The same general method is applicable in preparing similar tables for small gage tanks, and it is not discussed at length in this bulletin.

NECESSITY FOR CHEAP METHOD OF GAGING.

At present (1920) many operators in the Mid-Continent fields face a serious problem in finding an inexpensive method for gaging several wells running into a large gathering tank. One company has perhaps 2,000 wells and at many no gages have been taken except for one day when the well first came in. To equip each well with such a method as described on pages 182 to 186 would be very expensive. Although the daily individual well gage is preferable, the cost seems to prevent its installation. Meters and other devices have been suggested, but the cost is usually excessive. Some method should be devised that will at a reasonable cost give accurate estimates of a well's oil and water production per month. Such equipment would give a great impetus to taking well gages.

A gage of each well should be taken at least once a week, and from these gages a daily average struck for the month.⁶ Then, of the oil received at the storage tank from several wells for one month, each well can be credited with its proportionate production. For example, if the daily average of one well was 25 barrels a day, and the sum of the daily averages of all the wells delivering to this tank was 200 barrels, then this well made for the month twenty-five two-hundredths of the oil received at the gathering tank.

The writer suggests the following method for gaging a number of wells producing into one gathering tank. Mount a 50-barrel tank on a structure or have it so situated that the oil will drain from it to the large storage tank. Have the lead lines of various wells

⁵ Bowie, C. P., Oil-storage tanks and reservoirs, with a brief discussion of losses of oil in storage and methods of prevention: Bull. 155, Bureau of Mines, 1917, pp. 63-64.

⁶ When wells are old, small and steady producers, they need not be gaged so frequently.

pass over this tank and equip them with valves and connections so that the oil of any one well may be turned into the small gage tank or into the storage (stock) tank.

The drain to the storage tank would be at the bottom of the gage tank, so that the latter would drain dry. There should also be a bleeder in the very bottom of the gage tank. With such equipment a more accurate gage may be made. For example, close all the valves in the tank and allow the fluid from a certain well to run into it for a given time. At the end of that time read the height of the fluid. Drain off free water by the bleeder. Take a thief sample of the gross oil for a centrifuge test and measure the height of the remaining oil. This oil may now be run to the storage tank. With the data at hand, namely, the height of the total fluid produced in a certain number of hours, the height of the gross oil produced in the same time, and a centrifuge test of the gross oil, computations may be made giving a close estimate of the production of oil, water, and emulsion of this well for 24 hours.

To avoid use of a gage stick, a float and gage similar to that commonly used in water tanks may be installed. This float can be attached to a string with a weight on the other end, the string running over a pulley to the outside of the tank. The length of the string should be so adjusted that when the tank is full of fluid the weight rests on the outside opposite the bottom of the tank, and when it is empty the weight is at the top of the tank. The weight should move along a graduated stick so that the amount of fluid in the tank can be read at a glance.

Mr. Tom Cox, petroleum engineer, of the Empire Gas & Fuel Co., suggested that at each storage tank a structure be erected carrying a box similar to a sand-settling box, with a Lee V box recorder at the end, this instrument to record automatically the fluid that passed through the recorder. The lead lines from the different wells would pass across this box and be equipped with two valves in such a manner that the fluid of any well could be turned into the box or run direct to the storage tank, at the option of the gager. Then any well could be turned into the box and a record taken of its production.

One difficulty of such a scheme is that different wells make different quantities of oil and water, and the recorder may record differently on account of the difference in flow between oil and water. That could soon be settled by trial. A settling tank might be set up at each well and only the oil pass over the box, but this, again, involves expense.

Mr. Cox⁷ also suggests a device similar to the tailing samplers used in many ore concentrator mills, as follows:

Another method is placing a tilting measuring apparatus similar to the tailing samplers used at many ore concentrator mills. This apparatus tilts at an exact filled point and can be made to hold a definite predetermined quantity in each "pan." A recording counter will show the number of tilts, which can be read at any desired regular intervals, as the measuring device works only as filled and needs no attention. It can be made of light iron, is cheap and within range of possible installation even for very large properties, especially those where several wells are pumped into one gathering tank.

In case several wells are pumping into one tank a receiving box would have to be made and the piping connected up with valves, so that any particular well would be delivered into the receiving box, which would again feed to the tilting arrangement.

The sampling for water content must be made specially in each case, no matter what measuring apparatus is used.

PERFORATING AND SETTING SCREEN PIPE.⁸

Upon completion of a well in which there are two or more productive sands, the engineer with his complete log records can select the proper length of screen pipe or perforated and unperforated pipe to be set in the hole where perforated pipe is necessary. Placing a solid string of perforated pipe from the casing shoe to the bottom of the hole is not good practice, as mud can run in. The perforations should be opposite the productive sands.

In many properties it is not known just which of the sands from the water shut-off point to the bottom of the hole are productive, but as brought out on pages 20 to 24, effort should be made to get data on the contents of the different sands. When the sand directly below the casing shoe is known to be nonproductive, blank pipe can be set opposite this sand.

Again, as pointed out on pages 26 to 29, certain sands may contain a high-grade oil that the operator desires. From the logs and cross sections the perforations can be placed opposite the sand containing that oil with blank pipe opposite the lower-grade oil. When production of the heavy oil is desired the blank pipe can be perforated opposite the sands containing it.

In many areas running sands cause considerable trouble, and in such areas the relative merits of screen pipe and shop perforated pipe should be studied. Different size mesh should be tried and the results of different jobs recorded, particular notation being made of the effect of sanding up, production, necessity of cleaning-out jobs, etc.

⁷ Personal communication, Sept. 16, 1919.

⁸ For further details on perforated pipe and different types of screens, see Wagy, E. W., *Perforating casing and screen pipe in oil wells: Technical Paper 247, Bureau of Mines, 1920, 47 pp.*

Such work logically belongs under the engineer, for he has the complete records, and he should make himself more valuable to the management by accepting more and more responsibility and causing the superintendent to look to him in all such matters.

FLUID LEVELS AND TUBING DEPTHS.

GENERAL STATEMENT.

The fluid level may be regarded as the height of the fluid, either oil or water, or both, in the hole after the well has been allowed to stand. Often a well must stand 12 to 15 hours before the top of the fluid finds its own level. Generally the fluid level is recorded in feet as the distance from the top of the fluid to the derrick floor, or as the height of the column of fluid in the hole. When the level of one well is compared to another these figures should be considered in reference to sea level or the datum plane.

The level at which the fluid stands in the hole largely determines the proper tubing depth. The fluid level of a water from a sand is another factor that deserves consideration in a study of water problems. Often a well affording water to other wells is readily detected from old records giving the previous fluid levels of the different wells, the well at fault showing a higher level than the others. It is important that the collection of such records should not be delayed until after the water starts.

The collection of data on the fluid levels of drilling wells depends on the opportunity of testing a separate sand. In many wells such a test is not practicable, but whenever a fluid level can be easily determined the test should be made. The most reliable fluid level can be obtained when a test is made of a sand below the bottom of a string of casing which has shut off the waters above.

Where it is not safe to bail the casing dry for fear of its collapse (see p. 133), the well should be bailed down so far that the top of the fluid in the pipe is several hundred feet lower than the fluid level of the water in the sands; then if the water string leaks the water from behind the pipe will come in the hole. Evidently, if the test is to be reliable, the fluid level of the water in the sand must be known.

On a producing property the well-pulling gang can obtain data on fluid levels. These should be recorded in suitable forms (see Form 22, p. 224) from which monthly reports should be made. (Form 23.) This form contains space for recording the fluid level before and after a well is pulled, when to fish for sucker rods, replace a worn pump, or to bail the collection of fluid levels is started, their office each night. Little time and may later prove of considerable value.

The fluid level will generally show on the tubing as it is pulled from the well, as the fluid standing in the tubing will drain back into the hole as the tubing is pulled, and in a long string of large-sized tubing this fluid will raise the level considerably. In such event the top of the oil, as indicated on the withdrawn tubing, gives the fluid level rather than the level indicated by running in a bailer after the fluid in the tubing has drained into the hole.

On the other hand, the fluid in small-sized tubing will not raise the fluid level of the well appreciably. When a well is pulled immediately after a breakdown, the fluid level as indicated on the tubing may be much lower than the actual level after the well stands. To determine the true fluid level, a bailer can be run in just before the tubing is put back into the hole. The time between measurements of the level should be recorded.

Records of fluid levels have several uses, as follows:

1. Records of fluid levels from different sands may suggest the source of a water that appears in the well after it has been put to producing.

2. An unexpected rise in the fluid level may indicate the approach of edge water or breaking in of other waters.

3. Fluid levels may avoid skimming oil from the water in the hole.

4. The level of the oil from a sand may be used in studying the future oil production of the well.

5. Fluid levels aid in determining the proper tubing depth.

FLUID LEVELS MAY SUGGEST SOURCE OF WATER.

The first use suggested for fluid levels is in determining the source of water in a producing well that is making water. Several possible cases of such use are presented herewith.

Case I. When a well was being drilled, a certain sand was found to contain water, which, after standing several hours, rose to 400 feet from the surface and remained at that level. The well was drilled in this sand shut off behind the casing, and the well put to producing. The oil level stood 1,000 feet from the surface. A year later the well turned to water, and after several hours' stand the fluid stood out 400 feet from the surface. A reasonable inference is that this water was from the sand that had been tested. If the fluid had stood 1,000 feet from the surface, a reasonable assumption would have been that the water was from a different sand.

Case II. On the approach of edge w. the fluid levels may rise in wells nearest the edge-water line. In the American Petroleum Co., Coalinga, Calif., the fluid levels of the American approach of edge water, but unfortunately the record upon the ap-
the fluid

levels are not available. The great increase of oil production is shown in figure 25.

Case III. When several wells are making water, one well affording water to the others, the fluid stands higher in the offending well. This is shown in Bulletin 73 of the California State Mining Bureau,⁹ as follows:

The dotted line (see fig. 42) shows the levels at which the fluid stood in the various wells before the water troubles developed, while the solid line shows the levels about a year later, when the water trouble was serious. It will be

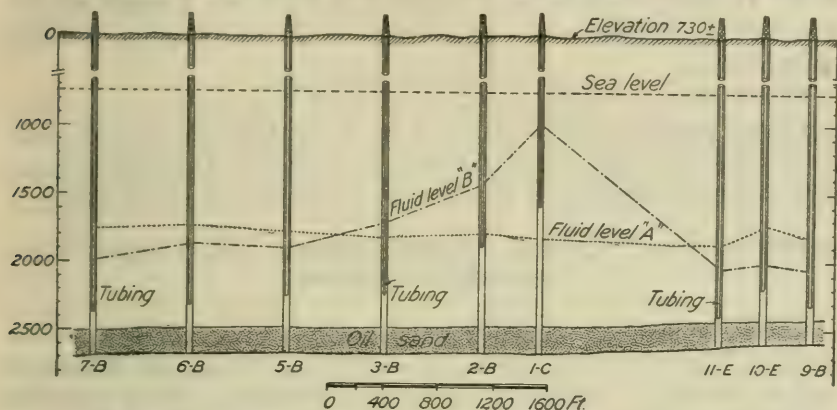


FIGURE 42.—Fluid level curves. Fluid level A represents the fluid levels of the wells prior to water trouble. Fluid level B shows level a year later, after water trouble started. No. 1-C was the offending well.

noted that the high fluid level in well 1-C points to it as being the source of the water trouble. This is the same conclusion afforded by the figures on production.

FLUID LEVELS MAY AVOID SKIMMING OF OIL.

Another use of fluid levels is to avoid skimming oil from the water in a well. When certain sands carry water under a low head and the oil sand has a low fluid level the tubing may be placed at a depth that will skim the oil off the water. For example, there may be 500 feet of fluid in the hole, the bottom 200 feet of which is water and the upper 300 feet oil. If the tubing were placed 400 feet off bottom the well would pump practically all oil and no water, but if it were lowered to below the water level much water would be pumped.

Because a well pumps no water the operator may assume the well is in good condition, but actually the water may be working into the oil sands and doing great damage. The operator should try, either by setting his pump deeper or running a bailer, to find whether there

⁹ First Annual Report of the State Oil and Gas Supervisor of California, 1915-16, Bull. 73, Calif. State Min. Bureau, 1917, pp. 115.

is any water in the bottom of the hole. Where oil has to work its way up through water an emulsion may form requiring special treatment to separate the oil from the water.

FLUID LEVELS AND FUTURE PRODUCTION.

The fluid level of the oil decreases as the supply is exhausted and may serve as a key to the rate of withdrawal of the oil for the height of the column of fluid exerts a certain pressure at the bottom of the hole. In short, the fluid level may be a guide to the decrease in rock pressure in pumping wells where there is no ready way to measure rock pressure.

Where there are tight sands, the oil level may stand near the top, but after pumping off the head of oil in the hole, the oil will come in slowly on account of the tightness in the sand. The rock pressure may still be strong enough to make the oil stand high in the hole.

STUDY OF FLUID LEVELS, TUBING DEPTHS, AND PUMPS TO INCREASE PRODUCTION.

Fluid levels are a valuable aid in establishing the best tubing depths. Operators frequently find that by lowering the tubing 50 feet or more they obtain an increased production. As an example, the following item is quoted from the California Oil World:¹⁰

Montebello, May 7.—Coming in quite a disappointment, the General Petroleum's Cruz No. 2 has been increased in production three times its initial output. This well was completed and put on the pump two weeks ago. The best the well would do was about 15 barrels a day. The tubing was lowered in the well and now it is doing 40 and 45 barrels daily.

The operator should experiment by lowering and raising his tubing, keeping daily records of the production, so as to judge closely the value of the changes. After various trials some depth will be found at which the well makes a greater monthly production, either because increased production while pumping or because of less time off for parted rods, or both. The relationship between fluid levels, tubing depths, and production should be carefully studied. Lost time due to parted rods means lost production and lost money. At least one company has lost several thousands of dollars each month by parted rods.

After the head is pumped off does the well pump down to a certain level above the pump, or does it and will it pump down to the working barrel? Will the pump lift more if the pressure of the weight of the column of fluid is reduced? Such questions should be answered.

¹⁰ California Oil World, May 8, 1919, p1 1.

Some wells may need pump assisters. Working conditions of a pump may be reproduced by use of a glass working barrel, the fluid pressure being realized by means of pressure pumps. The effect of each stroke of the pump may thus be watched.

In some wells the sands cave and a certain amount of fluid must remain in the hole to keep the sand from running in rapidly. To keep the well producing steadily and to avoid cleaning-out jobs, the fluid can not always be pumped low.

The suggestions offered above are for the engineer to apply to the wells in which he is interested.

SHOOTING OF OIL WELLS.

Two general purposes determine the shooting of oil wells by gelatin, nitroglycerine, dynamite, or other explosive: (1) Wells may be shot to overcome drilling or redrilling difficulties; (2) wells may be shot to increase the production from an oil-bearing stratum.

As regards (1), the engineer should have collected enough information on shooting to enable him to advise the superintendent or foreman on the size of the shot and where it should be set. The engineer's duty is primarily to give advice on the need of shooting, as shown by the results of shooting in other wells. Hence, this paper discusses shooting from this viewpoint of the engineer and does not describe the methods and mechanical details employed by oil-well shooters. For such details the reader is referred to the bibliography on oil-well shooting on page 200.

Careful measurements are necessary in making the shot at the right depth. If the original formation depths reported on the well log are 20 feet in error, a shot placed at an accurately measured distance below the surface would be of no value and might be harmful.

It is important to know that the hole is in condition for shooting so that the explosive can be set at the proper depth with little trouble. A premature shot may do great damage, ruining a water string or even junking the well beyond repair. In shooting sidetracked material, often the tools can not be run to the desired point, and then a small shot may be set off to make a pocket large enough for placing more explosive.

The size of the shot opposite a formation depends upon the thickness and texture of the sand, and the size of a shot for sidetracking tools or other material depends on the work to be done and the fluid in the hole. No larger shot than necessary should be used, as it may cause the hole to cave, split the casing unnecessarily, or do other damage. The size of the shot should be studied by the engineer.

SHOOTING OF WELLS TO OVERCOME DRILLING AND REDRILLING DIFFICULTIES.

In drilling or redrilling a well, tools or other material are often lost in the hole and can not be drilled past easily or they may fall into the hole later and stick the casing. Frequently this material can be broken up or driven out of the way by use of an explosive, thus permitting drilling to proceed with much less trouble.

In drilling or redrilling a well may be shot for the following reasons:

1. To sidetrack casing or tools that may be hindering progress.
2. To straighten a hole that has gone crooked on account of a particularly hard formation or lost lugs or lost tools.
3. To shoot two holes together. In redrilling a well, a bridge may have formed in the upper part of the old hole and caving formations may have fallen in and packed, with the result that the bit starts a new hole that branches away from the old one, and after 200 feet of drilling, the new hole may be 2 or 3 feet from it. If the old hole extends into the oil-bearing formations, top waters can enter the oil sand freely. Hence, it is necessary to shoot the two holes together before landing and cementing a water string.
4. To shoot sidetracked casing that may allow water to enter the oil sand. In many redrilling wells all of the old water string was not pulled. This may be sidetracked, and unless it has been plugged with cement to prevent its admitting the upper waters to the oil sand, a shot of sufficient size is necessary to break it up and bring the two holes together before a new water string is landed and cemented.
5. To shoot casing to allow cement outside the pipe. In plugging off bottom water it is often necessary to shoot any casing in the bottom of the hole in order to prevent, by cementing, bottom water from coming up outside as well as inside the pipe.
6. To part the casing at a depth above that at which it is to be pulled. In abandoning or redrilling a well it is sometimes necessary to pull a string of casing that is "frozen" near the bottom. "Vibration" is found and the depth above which the pipe is probably free is determined. The pipe may be parted at this depth by a light shot instead of by ripping or cutting the pipe. Such shooting may be harmful, especially if the well is to be redrilled.
7. To open the pipe opposite an oil-bearing stratum to allow oil to enter. This is sometimes done instead of perforating, splitting, or ripping the pipe.
8. To shoot hard formations instead of underreaming them. In a drilling well it is not always necessary to underream for every hard formation. Where only occasional underreaming is necessary a light shot may be used to enlarge the diameter of the hole so that the casing may follow.

SHOOTING OF WELLS TO INCREASE PRODUCTION.

It is a common practice in the Appalachian and Mid-Continent oil fields to shoot the oil-bearing limestones or hard sandstones of new wells in order "to get the well to produce." Such a shot often perceptibly increases the production. It is the engineer's duty to study the effects of the shooting. In a field where oil sand is soft but it is the practice to shoot every new well simply because of custom, some well should be put to producing without shooting and daily gages made of its production. Later the well should be shot and its production observed. The production records before and after shooting and a study of the cost of the work will tell whether shooting is necessary. After several such tests it may be seen that shooting does not help a well's production, and if it does not the practice should be abandoned, as it may injure the pipe, is dangerous, and is an additional expense. The well selected should be one that will serve for comparison; that is, one near another well and on the same part of the structure, so that normally both would produce the same amount of oil. In such shooting the casing must be pulled up the hole far enough to keep it from being injured by the shot.

In old wells shooting opposite the oil-bearing formation, as practiced at Garber, Okla., often stimulates production. This is true of hard oil-bearing formations producing a paraffine-base oil, as the pores in the sand near the hole clog with paraffine. Production curves (see pp. 17 to 19) of a well should be made showing its normal decline and its estimated future based on this normal decline. On this same curve can be plotted the actual future production following the shooting of the well to see whether the value of the increased production as a result of shooting offsets the money involved in the cost of the work, and the lost production while the well is closed in for shooting. Likewise, the engineer should consider any possible substitutes for shooting, such as heating or swabbing.

A shot should not be set off too near the bottom of the shoe of the water string, as it may make the water string leak or form cavities directly below the casing shoe, thereby letting top water into the hole. Certain operators in the Healdton field, Okla., have had trouble with leaky water strings caused by previous heavy shooting just below the casing shoe. Where it is necessary to shoot immediately below the water string, the shot should be as small as possible.

Care should be taken in placing a shot near the bottom of the hole, if the well is drilled to just above the top of a bottom water sand. A heavy shot may shatter the impervious bed above the water and allow the latter to flood the well.

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METHODS FOR RECOVERING MORE OIL FROM THE OIL-BEARING FORMATIONS.

An important field of work for the petroleum engineer is the study of methods of increasing recovery from oil-bearing formations. The startling estimate of Lewis¹¹ that 80 to 90 per cent of the oil underground is not extracted indicates that earnest efforts should be made to recover a larger proportion. Undoubtedly prices for petroleum will be higher in the future, and this should encourage the study of methods of increasing the recovery.

Such work belongs to the petroleum engineer. In this bulletin no attempt is made to discuss the different methods that may be used. Lewis¹² has discussed the use of the Smith-Dunn compressed-air process, the use of regulated back pressures, of gas or vacuum pumps, and of water displacement. Questions of shooting, swabbing, and cleaning out oil wells, the rate of pumping; the use of acids and electrical and steam heating to increase production should all be investigated by the petroleum engineer.

¹¹ Lewis, J. O., Methods of increasing the recovery of oil from sands: Bull. 148, Bureau of Mines, 1917, p. 26.

¹² Lewis, J. O., Methods of increasing the recovery of oil from sands: Bull. 148, Bureau of Mines, 1917, 128 pp.

FORMS FOR KEEPING RECORDS.

GENERAL CONSIDERATIONS.

Records are a necessity for the successful operation of any property. They should be kept in a logical and coordinated form, and for convenience in compiling the data the sheets should be standardized. Where practicable these records may be kept on letter-size sheets, either 8 inches by 10½ inches or 8½ inches by 11 inches, preferably the latter, as sometimes many figures must be recorded on the same sheet. Letter-size sheets facilitate a uniform system of files. The material should be filed so that any record can be found with little trouble.

So important is the manner of keeping accurate and complete records that a collection of the forms used by various companies was made. Several forms referring chiefly to individual well data are discussed in the succeeding pages.

In selecting and preparing forms for use on a property, care should be taken that the forms are a set applicable to the property. Many of the forms discussed below will have no value to certain companies, because the property is not operated in such a manner as to make the forms of use.

DRILLER'S TOUR REPORT.

The driller's tour report furnishes the data that serve as a basis for future correlation of formations and accurate determination of their occurrence. These forms should be properly and completely filled out and collected each day at all contract as well as at all company wells.

Two general types of reports are used; one, in book form, about 5 inches by 9 inches, of which Form 4 is a sample; and another, in pad form on letter-size sheets, 8½ inches by 11 inches, as Form 5.

Form 4 is a 24-hour report, each driller filling out his share. It is approved by the superintendent or drilling foreman and as a combined report is turned in each day. This type of report may save arguments among drillers, as in using one similar to Form 5, there is a chance to contrast the hole made by each driller, and one driller may claim more hole than he has actually made.

In a third type of report that each driller turns in is a separate report of his own work. Some companies use such a report in making up the time sheet for the pay roll. Under this system the driller is anxious that the tour report reaches the office each day.

FORM 4.—Form for daily drilling report; size, 5 inches by 9 inches.

Form 4.

No.-----

DAILY DRILLING REPORT.

 (Company.)
 Lease----- Division-----
 At----- Sec.----- Tp.----- R.----- Well No-----
 For 24 hours ending----- M.----- day of-----, 192-----
 Depth at last report----- Amt. casing in last report-----
 Hole made----- Amt. casing put in-----
 Present depth----- Total casing now in-----
 Kind of casing using----- Weight per foot-----

Formation.

From----- to----- ft-----
 From----- to----- ft-----
 From----- to----- ft-----
 From----- to----- ft-----
 From----- to----- ft-----
 From----- to----- ft-----
 From----- to----- ft-----

Water.

Struck at----- Ft. in formation of-----
 Rises in hole to within----- ft. from top. Kind of water-----
 Shut off water at----- ft. in formation-----
 With----- inch. Casing weighing----- lbs. per ft.
 Cemented at----- No. of sacks used----- Brand-----

Oil or Gas.

Struck at----- in formation-----
 Went through oil stratum at----- into-----
 Oil sand known as-----

Drillers and Tool Dressers.

Morning tour.		Afternoon tour.	
Driller-----		Driller-----	
Toolie-----		Toolie-----	
Total time drilling and bailing-----	hrs.----- min.	hrs.----- min.	
Cause of lost time-----	hrs.----- min.	hrs.----- min.	
-----	hrs.----- min.	hrs.----- min.	
-----	hrs.----- min.	hrs.----- min.	
-----	hrs.----- min.	hrs.----- min.	
Tools (rotary or cable)-----			
Approved-----		Superintendent.	
		(or Drilling Foreman.)	

Two or three carbon copies, depending on the number of offices desiring copies, may be made of Form 4, each on paper of different color. Where there is an adequate field force, an original and one carbon should suffice. The original goes to the field office for compilation of the well log; the carbon copy remains in the book. The carbon copies should be firmly attached in the log book so that they can not easily be detached and lost. On completion of the well, the log book should be labeled and filed.

The salient features that should be covered on each form are as follows: 1. The company, well number and location, and date; 2,

casing record; 3, formation encountered, with description; 4, water data; 5, notes on oil or gas; 6, names of drillers and tool dressers; 7, lost time, with reasons; 8, tools (cable or rotary); 9, remarks on any unusual features.

When work is started on a well, the exact location and elevation of the well should be written on the first sheet. The well's designation, such as number and location or other identification, should be marked on each sheet daily, and each report should be numbered consecutively.

The depth of the hole should be accurately known at all times. The casing record is important. The size, weight, and amount of pipe in the hole should be recorded and note made of any pipe pulled out or any indications of "freezing." Where the casing is cut, ripped, or perforated, a record should be made in detail. A clear statement should be made of the exact depth the casing is landed, the weight of the pipe, and where more than one weight, as, for example, "8 $\frac{1}{4}$ inch landed at 2,200 feet, bottom 960 feet—32-lb DBX, balance 26-lb. Aetna—all new."

When the water string is cemented the amount of cement used and the brand should be recorded. Certain brands may prove more effective than others, hence the necessity of a record for comparison later on. Note should be made of the length of time that elapses between the mixing of the cement and its placing behind the pipe, also the method used in cementing. Some cements take their initial set in a little over an hour, hence the need of getting the mixture behind the pipe as quickly as possible. With rapid setting cements, if more than an hour is used in placing behind the pipe, the strength of the cement may be weakened.

When a water string is tested (see section on Bailing Tests, pp. 131 to 134), the driller should record accurately the exact method of testing and give the results in detail, such as the depth of the hole, how determined, depth bailed out, length of time well stood for test, and results.

The driller should record accurately the top and bottom of each formation and give much care to recording formations, especially as the hole nears the oil sand. Sometimes the color of a formation is important in determining a marker; and the driller should observe whether a shale is tough or sticky, whether a sand is hard or soft, and should watch for pyrites of iron, for sea shells, hard lime "shells," etc. Samples of the formation should be collected (see Sampling of Formation, p. 20). Great care should be exercised in endeavoring to obtain a representative sample from the rotary ditch, but at best a sample off the rotary ditch may contain sand or shale from higher up the hole.

Cavey formations are important and their location should be known, as it may help the operator to keep the pipe free later in the drilling wells. Frequently a cavey formation can be overcome by pumping in a great deal of mud. If this is not done, the pipe may "freeze"—that is, bits of the formation may fall around the pipe and finally hold it tight. When casing freezes so that it will not move a new string of smaller size must be used in order to continue drilling, or redrilling is necessary, and as much as possible of the casing in the old hole must be cut and pulled. Such work means extra expense, hence good record should be kept of cavey formations. The driller should record all such information and any work done to keep the casing from "freezing."

All features relating to oil or gas are important. Scums of oil on the ditch of a rotary should be recorded, with some comment as to the degree of the "show." In a cable-tool well, where the bailer shows an oil scum or the washed sand shows a film, the fact should be recorded. If the bailer bubbles over the top when drawn from the hole, this should be reported, as it is often evidence of gas. The exact depths of these "shows" should be noted, although when there is much open hole below the pipe the driller should pay particular attention to the first "show" of oil or gas and note whether the "show" increases. Oil or gas from one sand may show in a well while the drill is passing through lower sands that are not productive, and such a "show" may be misleading. The driller should consider this possibility in recording the well log.

As regards water, the first signs of fresh, sulphur, or alkaline water should be noted. The exact location of a water zone should be known, especially water near the oil sand. If the fluid rises or falls when a sand is encountered, this fact should be recorded, and effort made to ascertain the level at which the fluid stands in the hole.

The names of the drillers and tool dressers should be recorded so that if the record is incomplete these men may be questioned. It frequently happens that several years after a well is drilled, a man who worked on the well can furnish information not previously recorded. This record will also keep the superintendent informed of the general distribution of his men and their activities. Lost time, and the reasons for it, should be known.

Remarks should be given covering any unusual features on the well, such as a detailed description of tests of the water string, of an oil, gas, or water sand, the loss of any tools in the hole, if they were recovered, or at what depth they were sidetracked, and their length. When a well is shot, the quantity of explosive used, the depth at which the shot was made, the reasons for shooting, the results, and the bottom of the casing shot when the shot was set off

should all be recorded. Notes should be made on the collapsing or freezing of pipe, use of jacks, broken engine or belt, recovery of casing, and, in fact, any feature out of the ordinary run of work.

FORM 5.—Driller's tour report.^a

No. _____

Well No. _____ Sec. _____

T. _____ R. _____

[Company.]

DRILLER'S TOUR REPORT.

On tour at 12 midnight.

19__

Casing.				Depth at beginning of tour_____ft.
Size_____	Weight_____	Brand_____	Shoe_____	Drilled during tour_____ft.
Amount put in_____ft.				Depth at end of tour_____ft.
Present amount in_____ft.				
Lost time_____hours. Cause_____				
Remarks_____				

Name of tool dresser.

(Signed) Driller.

On tour at 3 a. m.

Casing.				Depth at beginning of tour_____ft.
Size_____	Weight_____	Brand_____	Shoe_____	Drilled during tour_____ft.
Amount put in_____ft.				Depth at end of tour_____ft.
Present amount in_____ft.				
Lost time_____hours. Cause_____				
Remarks_____				

Name of tool dresser.

(Signed) Driller.

On tour at 4 p. m.

Casing.				Depth at beginning of tour_____ft.
Size_____	Weight_____	Brand_____	Shoe_____	Drilled during tour_____ft.
Amount put in_____ft.				Depth at end of tour_____ft.
Present amount in_____ft.				
Lost time_____hours. Cause_____				
Remarks_____				

Name of tool dresser.

(Signed) Driller.

Formations.	Note all characteristics of formations.
From _____ft. to _____ft.	Also oil, gas, water, etc.
From _____ft. to _____ft.	
From _____ft. to _____ft.	
From _____ft. to _____ft.	
From _____ft. to _____ft.	
From _____ft. to _____ft.	
From _____ft. to _____ft.	
Tools	

(Cable or rotary.)

^a Original, sheet 8½ by 11 inches, in pads.

Some companies have the drilling foreman instead of the superintendent approve the drilling record, the method depending largely, of course, on the way a company functions.

Form 5 is another type of daily report, or driller's tour report, embodying the same general features discussed above. This form is letter size for convenient filing and covers three tours of eight hours each. The superintendent using this form prefers to have no carbon copies at the well, and after the sheet goes to the office no record of past performances is available to the driller except in the well book in which the driller records the length of each separate joint of pipe, and the formation, and does his figuring. The field office files this sheet and sends to the main offices a compiled typewritten log, as discussed later.

Mr. W. B. Blodget, of the fuel department of the Atchison, Topeka & Santa Fe Railway Co., Fellows, Calif., prepared a set of instructions for drillers. These, or similar instructions, with a little educational work amongst the drillers, would soon bring about a highly desired, reliable set of records.

Mr. Blodget's instructions are essentially as follows:

INSTRUCTIONS.

A complete record of each driller's work is sent in every week to the head office.

Make your records clear and concise and observe the following rules as closely as possible.

DAILY REPORTS.

1. Use a sharp pencil and write carefully.
2. Pencils can be obtained from drilling foreman.
3. Always date report properly and sign your name.

DRILLING REPORTS.

1. In logging formation, be accurate in regard to depths above and below formation.
2. Always state presence of oil, gas, fresh water, salt water, sulphur, or any other peculiarity, giving depth where struck and where it ends.
3. Always note an unexpected rise or fall in fluid level, giving depths and whether oil or water is the cause.
4. In redrilling say: "Redrilled 625-650," etc.
5. In regard to work on well, aside from making hole, state nature of work clearly.

CASING RECORDS.

1. In landing casing, say: "Landed 8½-inch at 950 feet." Give weight and brand of casing, etc.
2. Give distance pipe is driven into formation.
3. In cutting, shooting, or ripping casing give depths above and below points of operation.
4. Be sure to state when drilling with perforated pipe.
5. In making daily casing report always cross out unnecessary word in regard to old or new or blank or perforated pipe.

PERFORATING RECORDS.

1. State whether shop perforated, by Brinkman or other method, or if screen pipe.
2. If shop perforated, give number of rows, size of holes, number of feet of perforated pipe, and length of shoe joint on bottom.
3. If perforated in hole, give method (Brinkman or otherwise), number of rows, size and distance between holes, and number of feet perforated, i. e., depths to bottom and top of perforations.
4. If screen pipe, give size of mesh, etc.

CLEANING OUT.

1. When cleaning out, where it is in the nature of a redrilling job and you think it is valuable information on drilling record, say: "Cleaned out 640 feet to 650 feet," etc. Otherwise, say: "Cleaned 20 feet," etc.
2. In cleaning out after a cementing job, state depth at which cement was found.

REAMING.

1. In underreaming, say: "Reamed 640 feet to 660 feet," etc.
2. Give formation in which the reaming is necessary.

BAILING RECORDS.

1. In bailing for test, either for cement job or to test a sand, say: "Bailed 500 feet to 600 feet (or whatever the depth was) to test sand at 620 feet or to test cement job."
2. Give anything else that will be of value in regard to results of test.

BRIDGING AND PLUGGING RECORDS.

1. State whether bridge or plug is of cement, clay, earth, brick, sacks, rock, or a combination of them, and give depths to top and bottom of bridge or plug.

CEMENTING RECORDS.

1. Say: "Cemented 10-inch at 650 feet," etc.
2. Give number of sacks of cement used.
3. Give method.
4. If mud is used, give number of tons and pump pressure, if using pump, or say: "Mudding with tools," etc.
5. State whether circulation was obtained or not.

ABANDONING CASING OR TOOLS.

1. Give date of abandonment of any tools, casing, or any material in hole.
2. Give depths to top and bottom of same.
3. Also give its length.
4. Give length of tools or other material lost in hole.

FORM 9.—Form for well log (reverse side).

[Size 8½ by 11 inches.]

Casing Record.

In., landed at	ft., cut at	ft., weighing	lbs., brand.
In., landed at	ft., cut at	ft., weighing	lbs., brand.
In., landed at	ft., cut at	ft., weighing	lbs., brand.

Oil and Gas Sands.

From	ft. to	ft.	From	ft. to	ft.
From	ft. to	ft.	From	ft. to	ft.
From	ft. to	ft.	From	ft. to	ft.

Water Sands.

From	ft. to	ft.	From	ft. to	ft.
From	ft. to	ft.	From	ft. to	ft.
From	ft. to	ft.	From	ft. to	ft.

Method of Shutting off Water.

In casing cemented at	ft. with	sacks of	cement.
In casing cemented at	ft. with	sacks of	cement.

Or (if driven)

In casing driven	ft. into	at	ft. shoe	ft. long.
In casing driven	ft. into	at	ft. shoe	ft. long.

Water tests.

State how long cemented water level, details of bailing and results.

Perforations.

Machine	-----			
From	to	rows	x	holes per foot.
From	to	rows	x	holes per foot.
From	to	rows	x	holes per foot.
From	to	rows	x	holes per foot.

Heaving plug (material) ----- at a depth of ----- feet.

Initial rating of well ----- Drillers.

Gravity of oil ----- water cut -----

Date well began prod. -----

Remarks: (Special features not provided for above.) -----

FORM 10.—Form for well log (reverse side).

[Size 8½ by 11 inches.]

Special Features.

Oil Sands.

1st snd. from	to	4th snd. from	to
2nd "		5th "	
3d "		6th "	

Water Sand.

1st snd. from	to	3rd snd. from	to
2nd "		4th "	

Drilling Record, Etc.

Size of casing.	Where landed.	Where cut.	Weight per foot.	Threads per inch.	Kind of shoe.	Make of casing.	Purpose of casing.

Water Strings.

Kind of cement.	Tons used.	Time of setting.	Method.	How tested.	Result.

Remarks
 Heaving plug—Material Length Where set
 Adapters Material Size

Perforations by

Machine.

From—	To—	No. of feet.	Rows.	Centers.	Holes.	Remarks.

Rating of well after 30 days
 Barrels of oil per day (24 hours)
 Per cent of water Gravity
 Drillers Tool dressers
 Remarks

Form 11 is a type of log form used by the California State Mining Bureau. This sheet measures approximately 8½ by 22 inches, but is folded to 8½ by 11 inches for filing. Additional information is typed on other blank sheets.

FORM 11.—Form for well log (front side).

[Size 8½ by 22 inches.]

Fill this blank in with typewriter. Write on one side of paper only.

California State Mining Bureau,

Ferry Building, San Francisco.

Log of oil or gas well.

Field.....Company.....

Township.....Range.....Section.....Elevation.....Number of well.....

In compliance with the provisions of Chapter 718, Statutes 1915, the information given herewith is a complete and correct record of the present condition of the well and all work done thereon, so far as can be determined from all available records.

Signed.....

Date.....Title.....
(President, Secretary, or Agent.)

The summary on this page is for the original condition of the well.

Oil Sands.

1st sand from.....to..... 4th sand from.....to.....
2d sand from.....to..... 5th sand from.....to.....
3d sand from.....to..... 6th sand from.....to.....

Important Water Sands.

1st sand from.....to..... 3d sand from.....to.....
2d sand from.....to..... 4th sand from.....to.....

Casing Record.

Size of casing.	Where landed.	Where cut.	Weight per foot.	Threads per inch.	Kind of shoe.	Make of casing.	Cemented.		
							Yes	No.	Number sacks.
.....									
.....									
.....									
.....									

Cementing or Other Shut-off Record.

Casing size.	Sacks.	Time set	Method.	Test and result (give water level and balling results).
.....				
.....				
.....				
.....				

Plugs and Adapters.

Heaving plug—Material.....Length.....Where set.....
Adapters —Material.....Size.....

Tools

Rotary tools were used from.....ft. to.....ft.
Cable tools were used from.....ft. to.....ft.

Perforations

State clearly whether a machine was used or casing was drilled in shop.

From—	To—	Size of holes.	Number of rows.	Holes for foot.	Machine—Shop.
.....					
.....ft.	ft.	.....	.....	.....	.....
.....ft.	ft.	.....	.....	.....	.....
.....ft.	ft.	.....	.....	.....	.....

Thirty days after completion well produced.....barrels of oil per day

The gravity of oil was.....degrees Baumé. Water in oil amounted to.....per cent.

Names of drillers.

Names of tool dressers.

Date drilling started.....

Date well was completed.....

Formations Penetrated by Well.

Depth to—		Thickness.	Name of formation.
Top of formation.	Bottom of formation.		

Form 12 is a form for recording data on a sheet of pocketbook size, 6 by 9½ inches, which the superintendent can carry in the field.

FORM 12.—Form of well record used in Oklahoma.

[Size 6 by 9½ inches. For use in loose-leaf field pocketbook.]

Well Records.

Notice.—Give top and bottom of all principal lime and sand strata.

Creek County. State, Okla.

Farm or lease, Maley Yarbola Well No. 27.

Location of section, 8 Town, 17 N. range 7 E.

Location on farm, SE. ¼ of section.

Rig commenced, ..., 191.... Built by

Drilling commenced, 1-4-16. Drilled by A. W. Leonard Drg. Co.

Drilling completed, 3-10-16.

Sand.	Top.	Bottom.	Remarks.
Layton.....	1,410	1,485	Oil & gas.
Jones.....	1,650	1,715	Little gas.
Wheeler.....	2,125	2,152	8 M. gas.
Skinner.....	2,245	2,285	Barren.
B'ville.....	2,554	2,648	Big pay.
Bottom B'ville.....		2,649	
Top Tucker.....	2,693		
Lead plug set at	2,698		
" " " "	2,628		
5-25-17, drilled out lead plug & started drilling deeper. One string of tools and one hundred thirty-five feet of pipe.			
Total depth 2,699			

Torpedo Record.

First shot, 80 qts. Date, 11-5, 1917. Size of shell, 3. Top of shot, 2,556.

Second shot.....qts. Date.....191.. Size of shell..... Top of shot.....

Third shot.....qts. Date.....191.. Size of shell..... Top of shot.....

.....Anchor.....Feet.....

.....

Casing Record.

Size.	Charge to well.	Put in well.	Pulled out.	Left in well.	Transferred before completed.	Left at well not in use.
	Ft. in.	Ft. in.	Ft. in.	Ft. in.	Ft. in.	Ft. in.
15½		500 3	500 3	.....	.....	.....
12½		729 2	729 2	.....	.....	.....
10		1,060 1	.....	1,060 1	.....	.....
8½		2,281	.....	2,280	.....	.....
6½		2,067 4	.....	2,048	.....	.....

Initial production, ... barrels.

The sums of the last three columns of casing record should equal "Charge to well" column.

..... Superintendent

DAILY INDIVIDUAL WELL PRODUCTION.

At a well making an appreciable production, daily well gages of oil and water are advisable. These can be recorded on Form 14. The wells of each section or tract are recorded on separate sheets and a total made of the production of each tract. The length of time a well produces during 24 hours can be recorded under "Hours pumped."

This form is used where the oil and water are gaged. Gross production represents the total fluid made by the well in 24 hours. The water is then drawn off and another gage taken, the fluid remaining being "gross or piped oil," that is, oil that is piped to the storage tanks. (See pp. 181 to 192 for a description of gaging, and pp. 181 and 182 for terms used.)

Inasmuch as the gravity of the oil from a well is constant over a considerable period, many companies do not make a gravity test oftener than once a month, but if a new sand has been perforated, the well deepened, or production obtained from a new sand it is often advisable to test the gravity daily. Where a well produces regularly, however, it is not necessary to make tests oftener than twice a month.

The gravity of an oil varies with the amount of water in suspension and in wells making a great deal of emulsion; the gravity test of the mixed fluid does not indicate the true gravity of the clean oil. Corrections¹⁴ can be made for this and should be, particularly if oil is sold on a gravity basis.

"Remarks" are for recording any special features of increased production, decreased production, abrupt change in water content, sanded up, pumping daylights, rods parted, and the reason for the well being "off," due to engine repairing, broken sucker rods, etc.

Form 15 is another type of report showing the estimated daily well production. This form can be used to record the oil production as determined by gaging a well periodically, from which its daily production is estimated (see pp. 184 to 186), and by using a centrifuge of a lead-line sample to determine the amount of water and emulsion. This same form may be used when gross production is actually gaged and a centrifuge test made of a lead-line sample. From these figures the barrels of clean or pure oil and total water can be computed. In this form of report it would be better to place the column for "Wells off pump" on the lower quarter of the page, to allow, on an 8½ by 11 inch sheet, more room for remarks.

¹⁴ Second Annual Report of the State Oil and Gas Supervisor, California State Mining Bureau: Bull. 82, 1916-17, p. 24 and fig. 14. The figure of this reference is a diagram which shows that the clean oil of a mixture, containing 90 per cent oil and 10 per cent water at 60° F. with a gravity of 19° B., will have a gravity of 20° B. at 60° F.

the gravity of the oil from a producing well is constant over long periods of time, and if the gravity is recorded only when it changes, considerable typing can be saved and unnecessary figures omitted from the record.

FORM 18.—Form for yearly summary of monthly productions.

[Size 8½ by 11 inches.]

.....Company.

OIL (BARRELS).^a

Well 15, Sec. 3,
T. 14 S., R. 10 E.

	1909	1910	1911	1912	1913	1914	1915
Jan.....		2,396	1,510 (20.6)	1,685	1,528	1,381	583
Feb.....		3,144	1,625	1,567	1,560	1,450	828 (20.7)
Mar.....		2,401	1,353	1,533 (20.4)	1,485	1,374	743
Apr.....	(^b)	2,255	1,898	1,455	1,557	1,358	835
May.....	4,921 (20.3)	2,111	1,695	1,650	1,478 (20.6)	1,401	905
June.....	3,341	1,655	1,703	1,610	1,380	1,288	650
July.....	3,690	1,777 (20.5)	1,738	1,603	1,415	1,328 (20.6)	955
Aug.....	3,092	1,363	1,635 (20.3)	1,520	1,337	1,305	943
Sept.....	3,680	1,366	1,603	1,490	1,282	1,132	1,085 (20.8)
Oct.....	3,305	1,603	1,940	1,580 (20.6)	1,277	1,333	1,085
Nov.....	3,193	1,536	1,770	1,530	1,313	1,375	658
Dec.....	2,435 (20.5)	1,683	1,818	1,545	1,425 (20.7)	930	1,233

^a Gravity shown in brackets.

^b Started producing May 2.

WATER (PER CENT AND BARRELS).

	1909	1910	1911	1912	1913	1914	1915
Jan.....		36	38	39	45	59	1,825
Feb.....		39	42	41	46	47	1,835
Mar.....		40	40	40	44	59	1,987
Apr.....		44	37	35	47	45	2,070
May.....	25	40	37	38	48	^c 2,234	2,365
June.....	24	39	43	36	59	2,187	1,920
July.....	30	21	41	37	32	2,292	1,830
Aug.....	36	47	29	37	40	2,206	2,767
Sept.....	37	28	29	44	49	2,183	2,488
Oct.....	40	42	33	51	52	2,142	2,520
Nov.....	40	37	33	34	59	2,173	1,640
Dec.....	37	26	46	43	71	2,178	2,442

^c Started to gage water.

Water is recorded directly below the oil-production figures and in a corresponding manner. In Form 18 the first part of the water record shows percentages during the period when water was determined by means of a centrifuge. After the actual gaging of water started, the water production is recorded in barrels.

The production records of the various wells can be bound, preferably in loose-leaf form, so that the sheets can be removed and figures added from time to time. The sheets for each well can be filed in numerical order according to the section or tract number.

At the front of each group of production records from a given tract, a map (see fig. 43) may be filed with some such scale as 1,000 feet to the inch, which permits the map to be letter size. This map should show the location and number of each well and its elevation.

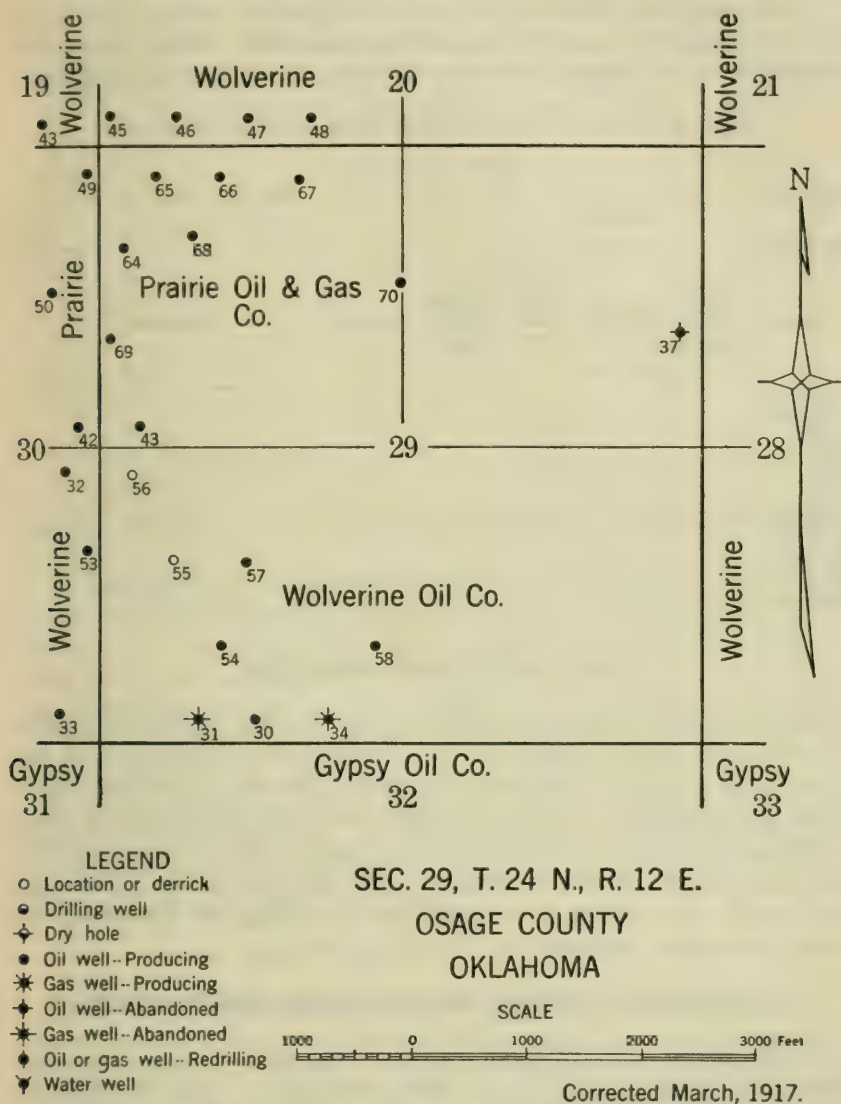


FIGURE 43.—Plot showing relative well locations, for insertion in book containing yearly summary of monthly publications. Size: $8\frac{1}{2}$ inches by 11 inches.

Following this map there may be a page giving information as to the date the property was acquired, number of acres, etc.; then a page showing the production per month of the tract and the date of completion, depth, initial production of oil and water and gravity

of oil for each well, the order of the wells being that of the dates of completion. The yearly summary of monthly production records should succeed these two pages, filled numerically. Generally, records for several sections or tracts can be bound in the same book.

Some companies have yearly production cards, such as Form 19, for recording the monthly production of a well. These cards are printed on heavy paper, and the cards for each well are kept together.

FORM 19.—*Card for summary of monthly record of production.*

[Size 4 by 6 inches.]

Well No. Division Sec. T. R.
 Location Year 19.

Month.	Estimated net production.	Per cent water.	Days idle time.	Average daily production.	Gravity.	Remarks.
January						
February						
March						
April						
May						
June						
July						
August						
September						
October						
November						
December						
Total						
Average						

WELL CUTS AND GRAVITIES.

Some companies make a centrifuge test of a lead sample only once a week, once every 10 days, or even once in two weeks, and at the same time make a hydrometer test of the gravity of the oil. Such tests are satisfactory where the wells are small producers, in good condition, and have no trouble from water. Form 20 is used by one company to record individual well data on the lead-line tests of a well. This form is prepared for recording the percentage of water, emulsion, and sand.

PRODUCTION OF WELL WHILE UNDER OBSERVATION.

When a well starts to make water, or just after a repair job, close watching of its production is often advisable. Daily production data may be kept on such a form as Table 4. This form can be used to considerable advantage to show at a glance the different outstanding features of the well. For instance, the gross oil made can be readily compared with the total amount of clean oil, as already discussed on page 188 in connection with Table 4.

MONTHLY TUBING RECORD.

The monthly tubing record (Form 23) shows the tubing or pump changes during a month. Even though no work is done on a well, the first five columns should be filled in to show the depth of the tubing during that month. If a well is pulled and the pump put back at the same depth, the fact should be recorded even though the depth is the same. Thus a complete monthly record is provided, and if a well is pulled several times during the month the fact immediately shows in this column. If the size of the pump is changed, the engineer should follow the production to see the effect. Under "Remarks," all information on why the well was pulled, crooked casing, etc., should be noted.

FORM 23.—Form for monthly tubing record.

[Size 8½ by 11 inches.]

Sec.....T.....R.....

..... Company.

Tubing Record.

..... 19

[illegible]

(Signed)

REPORT ON WORK ON WELLS.

Form 24 is used by one company. The company provides the gang foreman with Form 24 for reporting the work that has been done on a well. This serves a purpose similar to that of Form 22, the bailing and tubing record.

The Bureau of Mines heartily indorses the exchange of data between neighboring companies and particularly the exchange of information on line wells. Development of a field under one competent management would be the ideal plan, and if this can not be accomplished the nearest approach to it is to have each operator advised of the underground findings of his neighbor. Such cooperation will undoubtedly solve many problems and will benefit all parties concerned. On a form such as No. 27 can be recorded the data to be sent monthly to neighboring companies. On this sheet can be recorded the number of drilling, idle, producing, and newly completed wells. On a new completion the depth, initial production,

and gravity of a well is of interest to a near-by producer, and most often there is no reason for keeping this information secret.

In the case of line wells it is advisable to furnish the neighboring company with the log of the well immediately upon completion. On the lower part of the page the progress of the drilling and redrilling wells should be recorded. Such information generally includes the size of the casing being carried, the depth of the well, the date of starting a new well, and its location.

FORM 27.—Form for exchange of well data.

[Size 8½ by 11 inches.]

Well Data Exchange.

Month of 191..

Section.	Producing.	Idle.		Drilling.		New completions.				Abandoned.	Rigs.		Total.
		Producers.	Redrilling.	Active.	Suspended.	Well No.	Depth.	Initial Prod.	Gravity.		New.	Old.	
.....													
.....													
.....													
.....													
.....													
.....													
.....													
.....													
.....													
Total.....													

Drilling and Redrilling.

As of 19..

Drilling wells.	Redrilling wells.
.....	
.....	
.....	
.....	
.....	
.....	
.....	
.....	
.....	
.....	

..... Company.
.....19..

DAILY REPORT SHOWING IRREGULAR PRODUCTION FEATURES OF WELLS.

The superintendent of a large property with many producing wells should have his attention called to the most important features only. He should not be burdened with data which are of no particular value to the property's successful operation. He should be apprised of any sudden increase or decrease of production, any change of water content, or other equally important features.

Form 28 was designed for a superintendent, in which the important phases of the producing wells are laid before him each

day so that he may see them at a glance. The form can be filled by a clerk with the accurate daily production records before him; it is simple for the clerk to compare the present daily production with the normal production of a well. If the well has fallen off a certain number of barrels, this well should be placed on the sheet. Wells showing an increase in water content should also be recorded on this form. After the daily production figures have been reviewed for wells off, or low, or change in water, the sheet can be given to the superintendent, who can go into the details of the causes with the various foremen. The total daily production of the property should be reviewed and prepared for his attention.

FORM 28.—Form for daily report showing irregular production features of wells.

[Size 8½ by 11 inches.]

Daily Production.

..... 191.

[illegible]

COMPUTING WATER ANALYSES.

Form 3 (p. 105) is used for computing water analyses. Where only a few results must be computed, it may be cheaper to make this form on tracing cloth, from which white prints may be made. Usually a water analysis is reported in grains per gallon. By use of this form the factors are recorded so the engineer can carry the computations through on the same sheet of paper by means of a slide rule. It saves referring to tables and consolidates the computations to a single sheet. After the properties of the water are determined and recorded, the sheet may be filed for future reference.

PUBLICATIONS ON UNDERGROUND CONDITIONS IN OIL WELLS.

A limited supply of the following publications of the Bureau of Mines has been printed and is available for free distribution until the edition is exhausted. Requests for all publications can not be granted, and to insure equitable distribution applicants are requested to limit their selection to publications that may be of especial interest to them. Requests for publications should be addressed to the Director Bureau of Mines.

The Bureau of Mines issues a list showing all its publications available for free distribution as well as those obtainable only from the Superintendent of Documents, Government Printing Office, on payment of the price of printing. Interested persons should apply to the Director, Bureau of Mines, for a copy of the latest list.

PUBLICATIONS AVAILABLE FOR FREE DISTRIBUTION.

BULLETIN 134. The use of mud-laden fluid in oil and gas wells, by J. O. Lewis and W. F. McMurray. 1916. 86 pp., 3 pls., 18 figs.

BULLETIN 148. Methods for increasing the recovery from oil sands, by J. O. Lewis. 1917. 128 pp., 4 pls., 32 figs.

BULLETIN 155. Oil storage tanks and reservoirs, with a brief discussion of losses of oil in storage and methods of prevention, by C. P. Bowie. 1917. 73 pp., 21 pls.

BULLETIN 163. Methods of shutting off water in oil and gas wells, by F. B. Tough. 1918. 122 pp., 20 pls., 7 figs.

BULLETIN 165. Bibliography of petroleum and allied substances in 1916, by E. H. Burroughs. 1919. 159 pp.

BULLETIN 180. Bibliography of petroleum and other allied substances, 1917, by E. H. Burroughs. 1920. 170 pp.

BULLETIN 182. Casing troubles and fishing methods in oil wells, by Thomas Curtin. 1920. 48 pp., 3 pls., 15 figs.

BULLETIN 189. Bibliography of petroleum and allied substances, 1918, by E. H. Burroughs. 1920. —.

TECHNICAL PAPER 32. The cementing process of excluding water from oil wells, as practiced in California, by Ralph Arnold and V. R. Garfias. 1913. 12 pp., 1 fig.

TECHNICAL PAPER 38. Wastes in the production and utilization of natural gas, and methods for their prevention, by Ralph Arnold and F. G. Clapp. 1913. 29 pp.

TECHNICAL PAPER 42. The prevention of waste of oil and gas from flowing wells in California, with a discussion of special methods used by J. A. Pollard, by Ralph Arnold and V. R. Garfias. 1913. 15 pp., 2 pls., 4 figs.

TECHNICAL PAPER 45. Waste of oil and gas in the Mid-Continent fields, by R. S. Blatchley. 1914. 54 pp., 2 pls., 15 figs.

TECHNICAL PAPER 247. Perforated casing and screen pipe in wells, by E. W. Wagy. 1920. 48 pp., 6 pls., 12 figs.

TECHNICAL PAPER 68. Drilling wells in Oklahoma by the mud-laden fluid method, by A. G. Heggen and J. A. Pollard. 1914. 27 pp., 5 figs.

**PUBLICATIONS THAT MAY BE OBTAINED ONLY THROUGH THE
SUPERINTENDENT OF DOCUMENTS.**

BULLETIN 65. Oil and gas wells through workable coal beds; paper and discussions, by G. S. Rice, O. P. Hood, and others. 1913. 101 pp., 1 pl., 11 figs. 10 cents.

BULLETIN 149. Bibliography of petroleum and allied substances, 1915, by E. H. Burroughs, 1917. 147 pp., 15 cents.

BULLETIN 177. The decline and ultimate production of oil wells, with notes on the valuation of oil properties, by C. H. Beal. 1919. 215 pp., 4 pls., 80 figs. 30 cents.

TECHNICAL PAPER 51. Possible causes of the decline of oil wells, and suggested methods of prolonging yield, by L. G. Huntley. 1913. 32 pp., 9 figs. 5 cents.

TECHNICAL PAPER 53. Proposed regulations for the drilling of oil and gas wells, with comments thereon, by O. P. Hood and A. G. Heggem. 1913. 28 pp., 2 figs. 5 cents.

TECHNICAL PAPER 70. Methods of oil recovery in California by Ralph Arnold and V. R. Garfias. 1914. 57 pp., 7 figs. 5 cents.

TECHNICAL PAPER 130. Underground wastes in oil and gas fields and methods of prevention, by W. F. McMurray and J. O. Lewis. 1916. 28 pp., 1 pl., 8 figs. 5 cents.

INDEX.

A.		C.	
	Page.		Page.
Abbreviations. <i>See</i> Logs, graphic.		Cable tools. <i>See</i> Drilling.	
Adams, L. H., work cited.	124	Caddo field, markers in.	39
Air lifts. <i>See</i> Compressed air.		California State Mining Bureau, on	
Alkalinity, cause of.	91	fluid levels.	195
primary and secondary, defini-		on measurement during drilling.	130
tion of.	94	rules for testing water strings	
Ambrose, A. W., work cited.	134	by.	133
Analine dyes, as detectors, use of.	108,	Casing, collapsing pressure for, table	
115, 116		showing.	132
rate of flow of.	115	defective, oil losses from.	161
<i>See also</i> Flow detectors.		figures showing.	162,
Analyses. <i>See</i> Oil, analysis of; Wa-		163, 164, 165, 166,	
ter, analyses of.		167, 168, 169, 170	
Anderson, Robert, work cited.	150	depths for, chart of, view of.	60
Aneroid barometer, use of.	9	discussion of.	159
<i>See also</i> Elevation, wells.		Cattell, R. A. <i>See</i> Hammar, A. A.	
Appalachian fields, markers in.	22	Cementing. <i>See</i> Bottom water;	
Augusta field, Kansas, shutting off		Edge water; Middle wa-	
water in.	73	ter; Top water; Water	
Aurin, Fritz, work cited.	39	shut-off.	
B.		Centrifuge tests, accuracy of.	187
Bailing, record of, form for.	224	report of, form for.	223
tests during drilling.	131	results of.	188
Bates, Mowry, work cited.	41	Character formula, definition of.	91
Beal, C. H., work cited.	2,	Charleston, S. C., water at prop-	
162, 176, 178, 179		erties of, persistence of.	97
Bedridge field, wells in, cross section		Chlorides, detection of rate of flow	
of, view of.	42	by.	118
Beds, underground, position of, de-		disadvantages of.	118
termination of.	49	Coal beds, drilling through. <i>See</i>	
Bibliographies. <i>See</i> Compressed air;		Oil, losses of.	
Water, analyses of;		Coalinga field, bottom waters in,	
Wells, shooting of.		analyses of.	95
Birds Quadrangle, stereogram of,		chlorides and sulphides in,	
view of.	55	comparison of.	95
Blodget, W. B., acknowledgment to.	2	dye as detector in, use of.	117
instructions for drillers by.	206	edge water line in, figure show-	
Blue prints, from tracing cloths,		ing.	151
method of making.	37	view of.	150
Bottom settlements, definition of.	181	geology of.	150
Bottom water, definition of.	87	history of.	150
discussion of.	82	markers in.	40
shut-off for, figure showing.	99	middle waters in, analyses of.	96
for methods of.	143	mudding in well 90.	157
tests for.	127, 137	production in well 8.	152
Bowie, C. P., work cited.	190	well 31.	153
Bowman, Isaiah, work cited.	129	well 78.	157
Bridges. <i>See</i> Cement.		waters in, analyses of.	95
Brinton, W. C., work cited.	26	results of.	93, 94
Brunton compass, use of.	9	radicals in, reaction proper-	
Burrell, Logan, acknowledgment to.	2	ties of.	94
Burroughs, E. H., acknowledgment		water line in.	151-155
to.	2	rate of encroachment.	154
		water survey of, cost of.	90
		<i>See also</i> Water, analyses of, ap-	
		plication of.	

	Page.		Page.
Collom, R. E., acknowledgment to--	2	Drilling—Continued.	
on drilling progress charts----	55	redrilling to shut off water-----	143
work cited-- 36, 126, 140, 141, 142, 159		rotary method, advantages of--	157
Color. <i>See</i> Formations.		core barrel for, views of----	22
Compressor, air, equipment for, view		sampling, difficulties in-----	22
of-----	77	methods for-----	22-24
lifting water with, advantage of	75	time-depth reference chart for,	
bibliography on-----	78	view of-----	64
costs of-----	77	tests, advantages of-- 19, 20, 128, 129	
disadvantages of-----	77	weekly report of, form for-----	209
Congo red, as flow detector, use of--	112	well measurement during-----	129
Contour interval, definition of-----	46	<i>See also</i> Casing; Wells, depth	
Contour line, definition of-----	46	of; Wells, shooting of.	
Contour map, accuracy of-----	47	Dyes, as flow detectors, use of-- 113, 115-117	
description of-----	46	amount used-----	114
preparation of-----	46, 52	disadvantages of-----	107-108
uses of-----	48	merits of, comparison of-----	109
Convergence map, figure showing--	51	placing in well, method of-----	114
preparation of-----	50	sensitiveness of, determination	
use of-----	52	of-----	114
Core barrel. <i>See</i> Drilling, rotary.			
Correlation. <i>See</i> Cross sections;		E.	
Faults; Geology; Lenticularity.		Edge water, definition of-----	87
Coyote Hills field, peg model of,		discussion of-----	84
view of-----	52	encroachment of, figures showing-----	80, 84, 85, 151, 169
Cox, Tom, acknowledgment to-----	2	view of-----	150
on gaging storage tanks-----	191, 192	shutting off of, methods of-----	145
Cross sections, correlation of-----	38	tests for-----	127, 138
logs, advantages of-----	34	<i>See also</i> Coalinga field.	
plotting of-----	36	Elevation, wells, determination of--	8
cost of-----	36	Elliott, A. R., acknowledgment to--	2
line of, choice of-----	35	Emulsion, cause of-----	75
projection of well to-----	35	definition of-----	181
scale for-----	36	increase of, figure showing-----	75
<i>See also</i> Blue prints.		Engineer, duties of-- 5, 8, 21, 66, 135, 200	
Crumpton, T. J., work cited-----	185	Eosine, as flow detector, use of-----	112
Cushing field. <i>See</i> Water shut-off.			
		F.	
D.		Faults, effect on correlation of-----	41
Datum line, logs plotted from, discussion of-----	44	figure showing-----	41
figure showing-----	45	Field maps, data for collection of--	8
<i>See also</i> Peg models.		plotting of, figure showing-----	10
DeGolyer, E., acknowledgment to--	2	method of-----	9
work cited-----	124	Flow. <i>See</i> Water, rate of flow.	
Deussen, Alexander, acknowledgment		Flow channels, effect of-----	86
to-----	2	Flow detectors, difficulties with--	107
on warm oil as indication-----	124	requirements of-----	108
Dips, computation of. <i>See</i> Contour		use of-----	107
maps, uses of.		<i>See also</i> Chlorides; Dyes;	
Dole, R. B., work cited-----	110	Lithium salts; Nitrates;	
Donoghue, David, acknowledgment		Slichter electrical method.	
to-----	2	Fluid level, curves of, figure showing-----	195
Driller, tour report of, description of--	201	definition of-----	193
form for-----	205	records of, uses of-----	194
Driller, duties of-----	203, 206	Fluorescein, as flow detector, use of--	110
Drilling, cable method, sampling in--	21	Fluoroscope, description of-----	111
daily report of, form for-----	202, 208	use of-----	111
oil losses in, causes of-----	161-166	Formations, color of, significance of--	22
views of-----	162, 164	effect on drill-----	22
progress chart of, cards for, figure showing-----	65	samples of, containers for-----	20
discussion of-----	55, 63	examination of-----	25
view of-----	56	importance of-----	20, 25
		oil tests of-----	24

	Page.		Page.
Formations, color of, etc.—Continued.		Key beds. <i>See</i> Markers.	
<i>See also</i> Drilling, rotary		King, F. H., work cited.....	107
method; Drilling, with		Knoke, J. C., use of analine dye by..	115
cable tools; Symbols.			
France, fluorescein experiments in..	110	L	
		La Salle field, stereogram of, view	
G.		of.....	54
Gages, periodical, description of.....	184	Lead line. <i>See</i> Centrifuge tests.	
Gaging, costs.....	183, 186, 190	Lenticularity, effect on correlation	
methods of.....	179, 182-192	of.....	42
need for.....	179	Lewis, J. O., acknowledgment to.....	2
pumper's report, form for.....	215	work cited.....	16, 79, 121,
tank for, view of.....	165	139, 144, 149, 181, 178, 200	
terms used in, definition of.....	181	Liner, shutting off top water with..	142
<i>See also</i> Storage tanks; Thief.		Lithium salts, use as flow detectors..	119
Gage, table, for converting height of		Logs, cross sections of. <i>See</i> Cross	
fluid to barrels.....	189	sections.	
Garfias, V. R., statement cited.....	54	description of.....	209
Gas, escape of, effects of, views of..	151	form for.....	13-14, 210-214
Geologic structure, relation to pro-		discussion of.....	12, 15
duction, figure showing.....	177	graphic, abbreviations for.....	29
Geologic structure, correlation of		features of.....	26
surface to underground.....	38	historical, figure showing.....	33
<i>See also</i> Formations.		preparation of.....	32-34
Goodrich, H. B., work cited..	19, 144, 145	plotting of, directions for.....	29-32
Griswold, W. T., work cited.....	50	paper for.....	32
Gulf Coast field. <i>See also</i> Water,		scale for, discussion of.....	29, 30
analyses of, application		figure showing.....	30
of.		<i>See also</i> Abbreviations; Sym-	
		bols.	
H.		Losses, underground. <i>See</i> Oil,	
Hamilton, H. L., acknowledgment		losses of.	
to.....	2		
use of core barrel by.....	23	M.	
Hammar, A. A., work cited.....	41	McDonald, water shut-off, method	
Hammar, A. A., and Cattell, R. A.,		of.....	147
on lenticular oil sands.....	42	McDowell, J. C., acknowledgment to..	3
Hammar, A. A., and Scott, B. H.,		McDuffie, W. C., acknowledgment to..	2, 150
cementing job by.....	74	on costs of settling tanks.....	183
Hand level, use of.....	9	McLaughlin, J. A., on water line in	
Heald, K. C., acknowledgment to.....	2	East Side field.....	152
Heggem, A. G., work cited.....	139	McLaughlin, N. P., work cited.....	186
Hill, H. H., acknowledgment to.....	2	McMurray, W. F., cited.....	16,
on determination of sensibility		79, 139, 144, 149, 161	
of dye by.....	114	Magenta, as flow detector, use of.....	112
Hood, O. P., work cited.....	166	Markers, effect of unconformities on..	40
Huntley, L. G., work cited.....	50, 72	figure showing.....	40
Hydrology, chemical, Palmer's sys-		identification of.....	22, 39
tem.....	89	selection of.....	40
		<i>See also</i> Contour map, uses of.	
I.		Maps, data needed for.....	8
Intermediate water. <i>See</i> Middle		symbols for, description of.....	11
water.		figure showing.....	27
Isochore lines, definition of.....	50	standardization of.....	28
		use of.....	11, 26-29, 66, 125
J.		<i>See also</i> Contour map; Conver-	
Johnston, J., work cited.....	124	gence maps; Field maps;	
Johnson, R. H., work cited.....	50	Progress maps; Property	
		maps.	
K.		Matson, G. C., work cited.....	39
Kay, F. H., work cited.....	147	Merz, August, acknowledgment to.....	2
Kern River field, dye detector in,		Merz, Eugene, acknowledgment to..	2
use of.....	115	on comparative value of dyes.....	109
		Methylene blue, as flow detector, use	
		of.....	112

	Page.		Page.
Mid-Continent field, markers in----	22	Oil field, extension of, discussion of-----	175
Middle water, definition of-----	87	production of, future estimation of-----	176
discussion of-----	82	relation to structure, figure showing-----	177
shutting off, methods of-----	144	Oil sands, discovery of, method of-----	169-173
figure showing-----	83	figure showing-----	171
tests for-----	127, 137	deep, tests for, value of-----	174
<i>See also</i> Water; Water line.		production of, determination of-----	168
Midway field, property map of, view of-----	10	thickness of, study of need for-----	168
use of dye as detector in-----	116-117	upper, protection of-----	149, 156
Migration. <i>See</i> Oil, migration of.		Oil sand, water in base of, discussion of-----	86
Mills, R. V. A., acknowledgment to-----	2	methods of shutting off-----	147
migration experiments by-----	70	oil trapped by, figure showing-----	148
Mudding, economy of-----	158	tests for-----	128, 138
rules for-----	158	<i>See also</i> Oil and gas, sands.	
upper oil sands, discussion of-----	156	value of-----	149
Munn, M. J., work cited-----	50	Oklahoma, markers in-----	39
N.		Olinda field, use of dye as detector in-----	116
Nacatoch sand. <i>See</i> Caddo field, markers in.		P.	
Naramore, Chester, acknowledgment to-----	2	Pack, R. W., work cited-----	150
Neal, R. O., work cited-----	104	Packer, for repairing water string, use of-----	140
Nitrates, use as flow detectors-----	119	difficulties in-----	142
Nolan, E. D., acknowledgment to-----	2	Paleontology, use in correlation-----	38
work cited-----	175	Palmer, Chase, on cause of alkalinity and salinity-----	91
O.		work cited-----	89, 97
Oil, analysis of, use in correlation-----	38	Parsons, B. E., acknowledgment to-----	2
crude, daily receipts and deliveries, chart for-----	66	Peg models, datum line in, importance of-----	54
detection of different gravities in well-----	173	preparation of-----	52, 54
in drilling-----	24	use of-----	52
losses of, causes of-----	160-166	views of-----	52
migration of, experiments on-----	70	Perdew, W. E., acknowledgment to-----	2
figures showing-----	70, 71, 72	Permian Red Beds. <i>See</i> Oklahoma, markers in.	
views of-----	70, 71, 72	Pins. <i>See</i> Maps, symbols for.	
production of, future, determination of-----	196	Pipe, perforated, use of, discussion of-----	192
increase of-----	196, 199, 200	Plug, spiral, use in water shut off-----	144
indications of-----	122	Pollard, J. A., work cited-----	139
figure showing-----	123	Pomerania, use of chlorine method in-----	118
monthly report of, form for-----	219, 222	Potassium dichromate, as flow detector, use of-----	113
summary of, form for-----	220	Pressure of fluid in hole, effect on rock pressure-----	24
<i>See also</i> Wells, water in.		hydrostatic, effect of-----	169
Oil. <i>See also</i> Sands, oil in.		<i>See also</i> Casing; Rock pressure.	
Oil and gas, accumulation of, anti-clinal theory of-----	85	Production. <i>See</i> Oil; Oil and water; Oil fields; Water.	
determination of-----	48	Production curves. <i>See</i> Oil and water.	
sands, tests of, methods of-----	166	Property map, Midway oil field, view of-----	10
Oil and water, break between, discussion of-----	82	use of-----	10
gaging of, methods of-----	182-192	Pumper, daily gage report of, form for-----	215
production of curves of, figure showing-----	17		
plotting of-----	17		
production of, plots of, views of-----	57, 58		
production of, charting of-----	57		
<i>See also</i> Emulsion.			

R.	Page.		Page.
Radicals. <i>See</i> Water, radicals in.		Storage tanks, gaging of, record of, forms for	224
Records, data needed for	135	water content of, sampling of	192
old wells, importance of	12	<i>See also</i> Gaging.	
need of	6, 134	Suman, J. R., acknowledgment to	2
value of	178	on indication of warm oil	124
<i>See also</i> Logs; Maps; Wells, records of.		Swigart, T. E., acknowledgment to	2
Requa, M. L., acknowledgment to	3	on correlation of lenticular sands	42
Rice, G. S., work cited	166	Symbols. <i>See also</i> Maps, symbols for.	
Rich, J. L., work cited	55		
Rock, oil tests of, method of	24	T.	
Rock pressure, effect of	169	Tanks. <i>See</i> Gaging; Settling tanks; Thief.	
Rogers, G. S., work cited	104	Temperature, increase in, indication of	124
Rotary drill. <i>See</i> Drilling, rotary method.		Tests. <i>See</i> Bottom water; Drilling; Edge water; Middle water; Oil sand; Top water; Water string.	
		Thief, for sampling, figure showing	186
S.		Thiefing, samples from tank, discussion of	186
Saine, Tom, on rate of flow of aniline dye	115	Thomas, C. S., acknowledgment to	2
Salinity, cause of	91	Time lost in drilling, reasons for	61
primary and secondary, definition of	94	table showing	60
Salt Lake field, use of dye as detector in	116	Tools lost in hole, effect on production, discussion of	18
Samples. <i>See</i> Drilling; Formations; Storage tanks; Water, analyses of; Wells.		figure showing	19
Sampson, C. E., acknowledgment to	2	Top water, definition of	87
Sand, contents of, determination of, lenticular, correlation of, view of	78	discussion of	79
	42	shutting off, methods of	139, 140-143
Sand. <i>See also</i> Formations, sampling of, Oil; Oil sand; Water sand.		tests for	126, 136
Santa Fe Springs, well at, water difficulties of	73	Tough, F. B., acknowledgment to	2
Santa Maria field, peg model of, view of	52	cited	16, 20, 79, 131, 132, 135, 139, 142, 143, 144, 147, 149
use of dye as detector in	115	Trouble chart, discussion of	60
Sauer Dough sand, wells in, cross sections of, view of	40	<i>See also</i> Drilling, progress chart of; Time lost in drilling.	
Scott, B. H., acknowledgment to	2	Trudeau, J. A., acknowledgment to	150
Scott, W. W., acknowledgment to	2	Tubing, depths for, determination of	196
on rotary ore barrel	23	Tubing, record of, form for	224
Scale. <i>See</i> Logs, plotting of.		<i>See also</i> Casing.	
Screen pipe, use of, discussion of	192	U.	
Shidel, H. R., work cited	73	Udden, J. A., work cited	25, 38, 39
Shumate, J. G., acknowledgment to	3	V.	
Schlichter, C. S., work cited	106, 118, 119	Van der Leek, L., work cited	173
Slichter electrical method of flow detection	119	van der Linden, B. H., acknowledgment to	2, 150
difficulties of	121	van Eck, J. C., acknowledgment to	2
Settling tanks, costs of	183	Van Winkle, W., work cited	89, 90
figure showing	185	Venetian red, as flow detector, use of	113, 114
Solutions. <i>See also</i> Water.		W.	
Sperry, R. A., acknowledgment to	57	Wagy, E. W., acknowledgment to	2
Stereogram, preparation of	55	on lifting water by compressed air	75
use of	55	on oil losses from wild wells	162
views of	54, 55	work cited	192
Storage, receipt and delivery chart for, discussion of	64		

	Page.		Page.
Water, analyses of, application of	97-103, 104	Water string, repair of, method of	140
figure showing	101	tests of	129, 131
bibliography of	106	rules for	133
collection of samples for	103	Wells, R. T., cited	9
form for computing	105	Wells, abandoned, histories of, value of	15
geological value of	89	oil losses from, figure showing	164
interpretation of	90, 95	blowouts of, oil losses from	162
use in correlation	38	views of	151
<i>See also</i> Coalinga field; Hydrology.		cleaning of, record of, form for	226
encroachment of, effects of	75	correlation of, view of	40
figures showing	75, 76	cuts from, record of, form for	223
rate of	154	data on, exchange of, form for	228
relation to structure of	155	value of	227
<i>See also</i> Compressed air.		depth of, determination of	174
free, definition of	181	effect on near-by wells of	16
increased flow of, significance of	121	history of, discussion of	15
indications from	121-124	hours idle, report of, form for	227
in suspension, definition of	181	irregularities of, daily report of, form for	229
percentage of, determination of	18	location of, map showing	10
production of, gaging of	179	plat of, figure showing	221
properties of, concentration	94	<i>See also</i> Contour map, uses of.	
determination of	91	measurement during drilling, method of	129
persistence of	95	mudding of. <i>See</i> Mudding.	
radicals in, amount of, calculation of	92	production of, daily individual forms for	215, 217
reaction coefficients of	93	monthly individual form for	218
reacting values of	92, 94	production and trouble chart	59
rate of flow, determination of	106	progress chart	60
<i>See also</i> Flow channels; Flow detectors.		projection of. <i>See</i> Cross sections.	
shut-off of, discussion of	159	records of, forms for	201-299
experiments on	74	need for	12, 178
figures showing	81, 162-170	repair of	139
<i>See also</i> Bottom water; Edge water; Middle water; Oil sands; Plug; Top water; Water sands.		<i>See also</i> Water string.	
sources of	134-139	shooting of, bibliography on	200
determination of	98, 99, 100, 135, 194	discussion of	197-199
tests for. <i>See</i> Bottom water; Edge water; Middle water; Oil sand; Top water.		sites for, choice of	175
underground, damage from	74	water in, effect of	72
<i>See also</i> Gaging; Oil and water; Oil, migration of.		figure showing	180
Water level, different wells, relation of	107	work on, report of, form for	228
Water line. <i>See</i> Coalinga field.		<i>See also</i> Coalinga field; Drilling; Formations; Logs; Oil and gas; Water.	
Water sands, figure showing	80	Williams, W. A., acknowledgment to	2
lenticular, discussion of	86	Woodruff, E. G., acknowledgment to	2
figure showing	87	method of testing rock for oil	24
		Wootan, J. T., on use of dye as detector	116

